AD-A077 331 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 13/10
ANALYSIS OF THE COST OF VARIABLE WORKLOADS ON SHIPBUILDING.(U)
NOV 79 A H MAGNUSON , R W TERRY N00014-78-C-0411
UNCLASSIFIED VPI-AERO-103 NL

1 OF 3
AD
A077331

LEVEL II

(12)

AD A077331

COLLEGE OF ENGINEERING

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

BLACKSBURG, VIRGINIA

DDC FILE COPY

DDC RECEIVED NOV 29 1979 A

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

79 11 26 101

VPI-Aero-103

Final Report

Analysis of the Cost of Variable Workloads on Shipbuilding

by

A. H. Magnuson

and

R. W. Terry

November 1979

D D C
RECEIVED
NOV 29 1979
A

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

This work was sponsored by the Office of Naval Research, Contract No. N00014-78-C-0411.

79 11 26 101

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
6

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER
9

4. TITLE (and Subtitle)
Analysis of the Cost of Variable Workloads on Shipbuilding.

5. TYPE OF REPORT & PERIOD COVERED
Final Report, 1 Apr [redacted]978- 1 Oct [redacted]79,

6. PERFORMING ORG. REPORT NUMBER
14 VPI-Aero-103

7. AUTHOR(s)
10 Allen H./Magnuson ~~and~~ Robert W./Terry

8. CONTRACT OR GRANT NUMBER(s)
15 N00014-78-C-0411 Nw

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Department of Aerospace and Ocean Engineering &
Department of Industrial Engrg. and Operations Research, VPI&SU, Blacksburg, Va. 24061

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
12 250

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Arlington, Va. 22217

12. REPORT DATE
11 November 1979

13. NUMBER OF PAGES
242

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Information Systems Project
Office of Naval Research

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shipyard Production   Shipyard Workload
Shipbuilding Cost   Ship Construction Time

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The effect of shipyard workload variation on the cost of building ships has been analyzed. The results of four efforts are presented. The first major effort consists of an analysis of the effect of work density (i.e. worker crowding) on shipbuilding productivity and cost. The results show than an optimum least cost construction time and work-force level exist as a result of a tradeoff between work density effects and fixed costs. The second effort was an attempt to identify causes of shipyard productivity variation based — over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

406 922

JOB

on interviews with shipyard supervisory personnel. The third effort involved development of a framework for estimating transfer functions to describe how workload variation affects cost. This work is to be based on historical production and cost data. A description of adapting the Box-Jenkins forecasting methodology to the problem is presented. The fourth effort concerns development of a shipyard planning system to minimize cost of adjusting to workload variations. A review of current approaches to multi-resource/ multi-project planning models is given along with a proposed decomposition of the planning problem into strategic and tactical components. The strategic or long-range planning deals with aggregate issues such as organizational goals, long-range manpower planning and facilities expansion. The tactical component is more detailed and involves workforce allocation on a trade level to the various activities composing the construction of each ship. The tactical planning level is short-term detailed planning that takes into account inter-and intra-trade interferences, precedence relationships (proper sequencing) for each task and manpower allocation.

Accession For
NTIS GRA&I X
DDC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or special
A

Analysis of the Cost of Variable Workloads on Shipbuilding

by

A. H. Magnuson

and

R. W. Terry

ABSTRACT

The effect of shipyard workload variation on the cost of building ships has been analyzed. The results of four efforts are presented. The first major effort consists of an analysis of the effect of work density (i.e. worker crowding) on shipbuilding productivity and cost. The results show that an optimum least cost construction time and work-force level exist as a result of a tradeoff between work density effects and fixed costs. The second effort was an attempt to identify causes of shipyard productivity variation based on interviews with shipyard supervisory personnel. The third effort involved development of a framework for estimating transfer functions to describe how workload variation affects cost. This work is to be based on historical production and cost data. A description of adapting the Box-Jenkins forecasting methodology to the problem is presented. The fourth effort concerns development of a shipyard planning system to minimize cost of adjusting to workload variations. A review of current approaches to multi-resource/multi-project planning models is given along with a proposed decomposition of the planning

problem into strategic and tactical components. The strategic or long-range planning deals with aggregate issues such as organizational goals, long-range manpower planning and facilities expansion. The tactical component is more detailed and involves workforce allocation on a trade level to the various activities composing the construction of each ship. The tactical planning level is short-term detailed planning that takes into account inter-and intra-trade interferences, precedence relationship (proper sequencing) for each task and manpower allocation.

TABLE OF CONTENTS

Executive Summary

The work done under this contract is described in detail in the four Appendices, each of which is a self-contained report including introductory discussion material, lists of references, etc. This section summarizes the four major efforts described in detail in each appendix.

The first effort, Appendix A, deals with the effect of work density (worker crowding) on shipyard production rate, shipbuilding cost and time. A normalized production curve is developed using a hyperbolic tangent function to represent the dropoff in production rate as work density effects dominate. The normalization is accomplished using parameters obtainable from historical data. Total cost is taken as the sum of labor costs and indirect costs. Material costs are not taken into account because they are not significantly affected by work density (workload). A minimum cost exists because of the tradeoff between labor and fixed costs. The minimum cost point corresponds to an optimum workforce level and construction time. The results are interpreted quantitatively using shipyard data.

The second major effort (Appendix B) is entitled, "A Diagnosis of the Workload Variation Problem in Shipbuilding." As part of this phase of the research, a telephone interview was conducted in order to identify the primary preceived causes of productivity variation in shipyard operations. Several shipyards were also visited to identify specific causes of variations in productivity. The most frequently cited reasons for productivity variations were:

1) low labor progress,
2) low manning level,

3) craft incompatibility, and

4) delayed materials.

The first three of these causes were somewhat expected results and these topics were specifically identified on the interview questionnaire. Material shortages is an item that was not specifically listed on the questionnaire. However a number of managers listed it as one of the top three causes of variations in productivity. The complete results and specific questionnaire is available in the report along with an analysis of the components for a shipyard planning system.

The third effort (Appendix C) is entitled, "A Framework for Analyzing How Variations in Shipyard Workloads Impact Shipbuilding Cost." This report is divided into three principal sections. In Chapter II of the report quantitative definitions of workload and shipbuilding costs are presented. Chapter III presents the causal relationships of the impact of workload variations on shipbuilding cost. The costs identified include:

1) layoff cost,

2) cost of hiring new workers,

3) rehiring cost,

4) overtime cost,

5) workloads of less than 40 hours per week

6) subcontract cost, and

7) use of surplus workers to perform maintenance work.

In Chapter III an overview of the Box-Jenkins forecasting methodology is presented. In this chapter, a transfer function model is introduced and is used to find which of a large family of mathematical models best describe how a change in input affects output over time. This methodology

is developed in order to establish a set of difference equations that can be used to describe how workload variations dynamically affect shipbuilding cost.

The fourth report (Appendix D) entitled, "A Shipyard Planning System," is principally concerned with the development of a framework for a shipyard planning system which shipyards could use to minimize the cost of adjusting to workload variations. Chapter I provides a brief introduction to the planning problem in a shipyard. The complexity of the task of building a ship is brought out, resulting in the identification of the system as a multi-resource/multi-project planning system.

In Chapter II, a brief review of current approaches to multi-resource/multi-project planning models is given. The factors identified in the use of these models are (1) the data requirements which requires that the user specify the precedence relationships among the various activities in building a ship, and (2) the evolutionary nature of the shipbuilding process. The first factor results in a combinatorial problem too large and too expensive for any single heuristic planning model to handle. The second factor posses a more difficult barrier in that the specification of the sequence in the performance of some important construction activity cannot often be identified a priori at planning time. Such precedence relationships tend to evolve over time as the work on the various ships in the yard progresses. Thus, it is necessary to decompose the planning problem.

Chapter III of the report discusses the theoretical framework under which the Multi-Resource/Multi-Planning Problem can be decomposed into solvable parts. The planning problem is broken down into its strategic components and its tactical components. The strategic planning problem spans a

long-range planning horizon and deals with aggregate issues of organizational goals, long-range manpower planning, facilities expansions, etc. A clear understanding of how workforce levels and project completion dates impact cost is necessary for the planning performed at the strategic level. Such costs include the cost of late deliveries, materials, and labor including the cost of hiring and firing. The strategic planning program, modeled as a mixed integer quadratic programming problem, is discussed in detail in Chapter IV. A precedure in solving this problem is also described in this chapter.

The tactical planning problem, on the other hand, is more detailed and would involve the development of plans on how each trade's workforce should be allocated to the various activities necessary for the construction of each ship. The planning at this level spans a shorter planning horizon and requires that the tactical planner recognize that (1) both intertrade and intratrade interference can cause substantial productivity losses, (2) failure to consider strict precedence relationships can cause unnecessary delays and costs to be incurred, and (3) overtime can be used when it is cost effective to do so. A complication that is inherent to the tactical planning process is the random variation in activity duration times and the uncertainty regarding the sets of activities which will actually be necessary. Thus, it is imperative that the tactical plan be revised periodically. The tactical planning problem is formulated as a resource-constrained cost-CPM type of problem and solve via a procedure based on the model developed by Dar-El, et. al. Both the formulation and the solution procedure are discussed in greater detail in Chapter V.

APPENDIX A

WORK DENSITY AND ITS EFFECT ON SHIP CONSTRUCTION COST AND TIME*

Dr. Allen H. Magnuson
Aerospace and Ocean Engineering Department

and

Dr. Robert W. Terry
Industrial Engineering and Operations Research Department

Virginia Polytechnic Institute and State University
Blacksburg, Virginia

ABSTRACT

A quantitative analysis of ship construction costs as a function of construction time and workforce level is presented. A normalized production curve is developed using a hyperbolic tangent function to represent the dropoff in production rate as work density (crowding, worker interference) effects dominate. The normalization is accomplished using parameters obtainable from historical data. Total cost is shown to be the sum of labor costs which increase with work density and indirect costs proportional to construction time. A minimum cost exists as a result of the tradeoff between the two major cost groups. The minimum cost is associated with an optimum workforce level and construction time. The results are interpreted quantitatively using shipyard data.

INTRODUCTION

Any meaningful quantitative analysis of the ship construction process to predict costs and construction times becomes very difficult because of the large amount of factors affecting the outcome. In addition, shipbuilding is an activity that must be differentiated from other types of manufacturing such as automobile production. The large body of knowledge on mass-production has only limited applicability to ship construction where the "production runs" are restricted to tens of units at most (Reference 1). Therefore, the analyst must depend primarily on his own resources in developing a methodology to attack a specific problem. To make the present problem tractable, the limited scope of the work will be delineated, terms will be defined as needed and simplifying assumptions will be stated.

This paper is not concerned with ship design or design optimization. The starting point of the analysis is the following: consider a ship or series of identical ships to be built in a given shipyard where the construction process or procedure and facilities are specified and held constant throughout the construction period. The ship design is fixed: that is, the configuration of the object to be constructed is fully defined by suitable drawings to the necessary level of detail. Once the design, the number of ships to be built, the construction process and available facilities are known, then one may make the basic assumption that a definite cost is associated with the operation (as differentiated from the price). The construction time may also be predicted assuming the shipyard planners schedule the work and it is performed subsequently according to the usual work pace arrived at as a result of experience. This construction time can be assumed to be the nominal optimum construction time. (The construction time for the purposes of this paper is the time interval between contract award or other authorization to commence construction to the date of delivery and acceptance by the customer.)

If for some reason the normal construction process must be accelerated or slowed down, then one may expect the costs to increase. For example, the shipyard planners may wish to stretch out the work, lengthening the construction time, to avoid laying off workers to maintain workforce stability or continuity in times when the overall workload is light. Conversely, the construction time may be shortened when the yard has an extensive backlog of work. Accelerating the normal work pace will require an increase in the workforce. The increased workforce will not be able to work as efficiently because of limited access to the fixed production facilities, which are geared to the normal workload. In addition, simple overcrowding may occur in limited workspaces, particularly in the outfitting phase. The overload problem then is characterized by the concept of <u>work density</u>, a term first used by Frisch in Reference 1. Work density (or more precisely, worker density) can be defined as the number of workers per unit work area. Most if not all phases of ship construction are performed in a restricted or at least well defined work area. Under normal workload conditions definite values can be assigned to the work density for each type of activity such as pipefitting, hull fabrication or electrical wiring. One should be able to compute a global (shipyard-wide) mean work density for a given type of ship if the skill or trade mix is fixed.

If the work period is extended beyond the nominal optimum, cost will increase because of indirect or overhead-related costs. These fixed costs, which are proportional to the time of construction, include items such as taxes, depreciation, utilities, etc. Indirect costs include all costs that cannot be directly charged to any one contract (Reference 2). It is clear then that the minimum cost and its associated optimum construction time are both the consequence of the tradeoff between labor costs affected by work density effects and fixed carrying costs. The purpose of this paper is to analyze this relation in a quantitative way.

Before starting with the analysis, a review of the usual cost estimating procedure used by planners or Naval Architects is instructive. The

* Paper presented at the Eighth Annual DOD/FAI Acquisition Research Symposium, May 2, 1979, Newport, R. I.

cost estimation procedure used in bid preparation and design studies is described by Benford in Reference 2. To summarize briefly, labor and material costs are estimated on the basis of weights (or horsepower in the case of propulsion machinery) for four major categories:

1. Steel Hull
2. Outfitting
3. Hull Engineering (Deck machinery & Equipment)
4. Machinery (Main Propulsion and Auxiliary)

The weights are, in turn, estimated using the cubic number and other parameters describing the ship size, configuration and proportions. Benford (Reference 2) includes a miscellaneous direct labor cost to cover drafting, purchasing, scheduling, material handling, etc. This is computed as a percentage of the direct labor costs. Overhead or indirect costs, defined as including all costs that cannot be directly charged to any one contract are taken as a percentage of the direct plus miscellaneous labor costs. Benford (Circa 1960) uses an overhead rate of 70% on this basis. Combining the above four functional categories, three major cost groups can be identified:

1. Materials
2. Direct Labor
3. Overhead

Mack-Forlist (Reference 3) gives the following percentage breakdown of costs for three types of ships:

	Tanker	Cargo Ship	Destroyer
Material	55	55	40
Labor	25	23	30
Overhead	20	22	30

The overhead rate given by Mack-Forlist is higher than Benford's probably because Benford's miscellaneous labor cost category was included in Mack-Forlist's overhead. The exact cost breakdown will vary from shipyard to shipyard depending upon the accounting system used. At any rate, the overhead rate at a given yard is usually given as a fixed percentage of the labor costs. This rate is based on an average workload at the yard. In this study a more general view of overhead or indirect costs will be used that explicitly takes into account the variable workload. One would expect that in an underutilized yard fixed expenses would have to be prorated over a smaller workload thus increasing the overhead rate. Conversely, an overloaded yard should have a lower overhead rate.

This study will be concerned with labor costs as affected by work density and overhead costs. Material costs will be disregarded as they are not affected by workload or construction time. (Any carrying charges for materials can always be included in the overhead category.)

One major problem in an analysis of this kind is how to define the governing parameters or variables. The variables must be measurable quantities that have some clearly understood meaning. In addition, cause and effect relationships must be established. That is, one must distinguish between independent and dependent variables. For this problem the independent variables are the workforce level (W) and the construction time duration (T). These are the key variables the planner may wish to manipulate to compute costs when stabilizing the workforce or to expedite work in an overload condition. The workforce level is taken as an average over the construction period T and refers to production-related workers (those not charging to overhead). The dependent variables (the ones the planner wants to predict as a function of W and T) are:

C_T - Total Cost
C_L - Labor Cost
C_I - Indirect Cost
R - Production Rate
K - Unit Labor Cost

Key parameters characterizing the ship or ships to be constructed, the production facility and the construction process are:

K_o - Low work density unit labor cost
R_∞ - Maximum production rate
W_{cr} - Critical workforce level ($=K_oR_\infty$)
A - Work area
α - Critical workforce density ($= W_{cr}/A$)
N - Number of units (ships) to be constructed
W_{eq} - Equivalent workforce level for indirect costs
β - Dimensionless parameter for indirect costs ($= W_{eq}/W_{cr}$)
T_{min} - Minimum construction time ($= N/R_\infty$)
C_{LO} - Zero density labor cost ($= NK_o$)

Many of the above parameters are used to normalize the dependent and independent variables by forming dimensionless ratios, e.g. W/W_{cr}, R/R_∞.

NONDIMENSIONAL PRODUCTION RATE

To start, consider the case where some relatively simple construction task is being performed. For example, fabrication of a simple subassembly for a ship such as a thrust bearing foundation or a support pillar. That is, some activity where the labor force is homogeneous so that little or no specialization is required. Later, the results of the analysis will be applied on a shipyard-wide basis where the workforce is non-homogeneous. On a shipyard-wide level, the workforce skill trade mix for each yard will vary; however, each yard will have a characteristic production rate reflecting its workforce distribution. In addition, the study will assume that the workforce is already thoroughly trained so that effects of learning can be ignored. First consider the case where the work density is very low, i.e., where there is no worker interference or crowding. The input is the number of workers (W), say in worker-days per day; that is, the workforce level. The output is the number of units produced per unit time (production rate), which will be designated R. For example, R may be the number of foundations fabricated per day. The larger in magnitude or more

complex the construction task, the lower the rate of production. For a given construction task, the production rate is proportional to the workforce level because in the low work density limit there is no worker interference. For example, if the workforce is doubled, the production will also double. This relationship may be expressed as a single equation:

$$R_o = W/K_o, \qquad (1)$$

where K_o can be considered an index of the task magnitude and complexity. This equation states that the production rate (R_o) is proportional to the workforce level (W) and inversely proportional to the complexity (K_o). Equation (1) can be rearranged to solve for K_o:

$$K_o = W/R_o \qquad (2)$$

From Equation (2) one sees that the complexity K_o has the units of W divided by the units of R. For example if W is in man-hours per day and R is in units produced per day, K_o will have units of man-hours per unit produced. That is, K_o is the amount of labor required to produce one item in the low-density limit. The index K_o is then proportional to the low density labor cost.

In practice, almost all tasks are performed in a more or less confined work space, where worker interference will increase as the number of workers increases. This will lower the increment in productivity as W increases. This effect is indicated in Figure 1 where the productivity curves level off or bend downward for increasing W. This Figure, taken from Ref. 1, provided the basis for this study.

Note that because of the downward curving of the lines in Figure 1 the production rate no longer doubles if the number of workers is doubled.

The type of curve shown in Figure 1 has the same general shape as a hyperbolic tangent (abbreviated tanh). The curves in Figure 1 resemble hyperbolic tangents because they start out linear (straight lines) for very small values of the argument (W), and eventually level off to a final constant value for large values of W. All of the curves in Figure 1 can be collapsed into a single hyperbolic tangent curve if the ordinate (R) and the abscissa (W) are suitably normalized. One may normalize the ordinate by dividing R by its final maximum (worker saturated) value, denoted as R_∞. Then the final value of the normalized production rate (R/R_∞) will be one. One may normalize the workforce level W by dividing by W_{cr}, the critical number of workers. The parameter W_{cr} can be defined (more or less arbitrarily) as the number of workers where the production rate reaches 76.2 percent of the final value of R_∞, as indicated in Figure 2. This defines W_{cr} as the number of workers where the argument of the hyperbolic tangent (W/W_{cr}) is equal to unity. This definition of W_{cr} characterizes the falling off or break in the hyperbolic tangent curve. The normalized production curve is shown in Figure 2. This curve, in effect, collapses all the curves shown in Figure 1. The normalized curve in Figure 2 is written in equation form as

$$R/R_\infty = \tanh\,(W/W_{cr}) \qquad (3)$$

The maximum value of the production rate R_∞ can be related to the low density unit labor cost K_o and the critical workforce level W_{cr} by taking Equation (3) for small values of the argument (W/W_{cr}) and setting the result equal to Equation (1). Writing (3) for small values of the argument gives after rearranging:

$$R = (R_\infty/W_{cr})\, W \qquad (4)$$

Comparing (4) with (1) indicates that

$$W_{cr} = K_o R_\infty. \qquad (5)$$

This result shows that W_{cr} interrelates the low density labor cost and the high density maximum production rate.

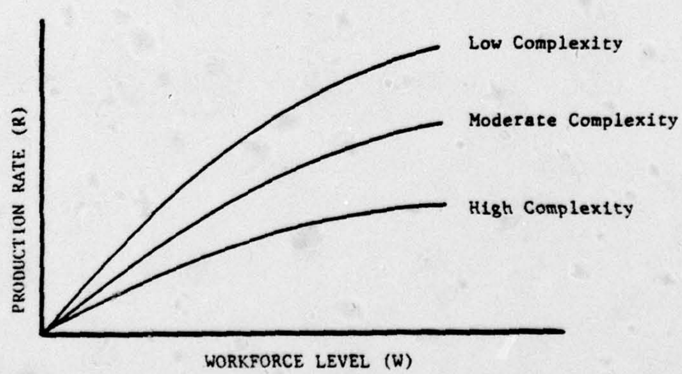


Figure 1. Effect of Work Density on Productivity

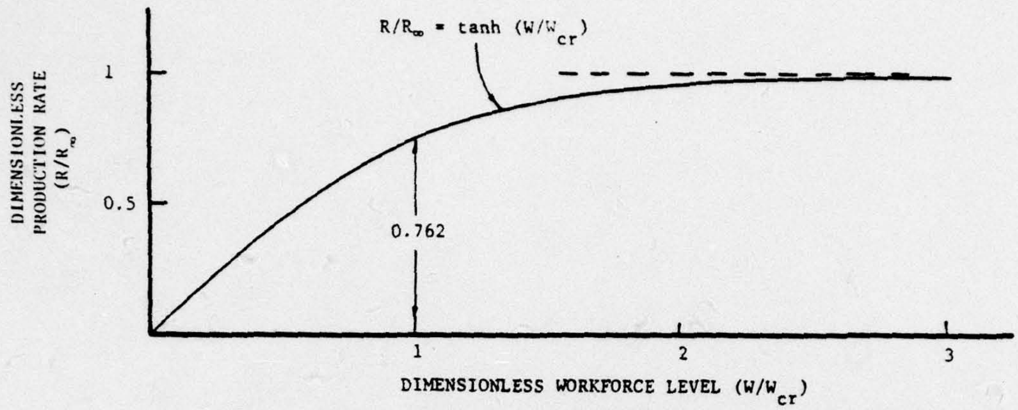


Figure 2. Normalized Production Curve

One may also relate R_∞ and W_{cr} to measurable parameters. These parameters are the low-density complexity or cost K_o, the work area and the critical work density. The complexity K_o has been defined earlier in Equation (2). The work density will be defined more precisely below. To start, consider R_∞. One would expect the maximum or final value of the production rate to decrease with the complexity K_o, similar to the way it did in Equation (1). That is, one would expect R_∞ to be inversely proportional to K_o. In addition, R_∞ must be proportional to the available work area A. The work area is an easily measured quantity, as most construction tasks are performed in a restricted work space. Accordingly, one may write the equation for R_∞ as follows:

$$R_\infty = \alpha A/K_o, \qquad (6)$$

where α is the proportionality constant. The parameter α will vary depending upon the construction task, type of process, equipment used, etc. One may relate α and A to the expression for W_{cr} in (5) using (6) to obtain

$$W_{cr} = \alpha A. \qquad (7)$$

Solving Equation (7) for the parameter α gives

$$\alpha = W_{cr}/A. \qquad (8)$$

Equation (8) indicates that α is the critical work density or workforce density, i.e., the critical number of workers per unit of work area. (The density is given as an area density rather than a volume density as it seems more natural in this application.) Equation (8) can be used to compute W_{cr} in (7), as the critical work density can usually be estimated for a given task. For example, in the case of non-mechanized ditch digging, one would expect the critical work density to be around 1.0 worker per square meter, based on the amount of space needed to manipulate a pickaxe and shovel without interfering with adjoining workers.

The final equation characterizing the construction process can be written by substituting the expressions for R_∞ (Equation 6) and W_{cr} (Equation 7) into Equation (3). After some minor rearranging, one has

$$R = (\alpha A/K_o) \tanh (W/\alpha A). \qquad (9)$$

Note that the units of the variables in Equation (9) must be consistent. For example if the units of K_o are in man-hours per unit produced and the units of R are in units produced per day, then W must be in man-hours per day.

COST ANALYSIS

Referring back to Equations (1) and (2), one sees that the inverse slope of the productivity curve gives the labor required to produce a single unit or the unit labor cost. For the more general case where the work density is taken into account, the labor cost (denoted K) can be expressed in a form similar to Equation (2)

$$K = W/R, \qquad (10)$$

where R is given by Equation (3). Substituting Equation (3) into (10) gives after some manipulation

$$K/K_o = \frac{(W/W_{cr})}{\tanh (W/W_{cr})}. \qquad (11)$$

One sees that the actual labor cost relative to the low-density cost (K/K_o) is only a function of the ratio W/W_{cr}. Equation (11) is plotted in Figure 3. One sees that K/K_o is close to unity for small values of W/W_{cr}, with the curve increasing to 1.313 for $W/W_{cr} = 1$. Below 0.5 the effect of work density is fairly weak. At the critical workforce level the labor cost is 31.3% higher than the low density level. In fact, this observation provides an alternative method of defining the critical workforce level.

As discussed in the Introduction, ship construction costs are generally broken down into three major categories: direct labor, indirect costs and material costs. Since material costs are not affected by workforce level or construction time duration, for the purposes of this study they are considered to be constant, and will be

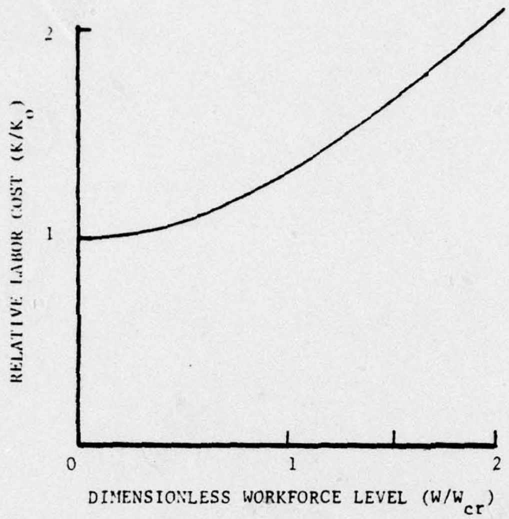


Figure 3. Relative Labor Cost Versus Workforce Level

disregarded. The simplified cost equation may then be written as follows:

$$C_T = C_L + C_I, \qquad (12)$$

where C_T is the total cost, C_L is the direct labor cost and C_I are indirect costs. One may write the direct labor cost for constructing N identical units (ships) as

$$C_L = NK, \qquad (13)$$

where K is the unit labor cost. One may also write the labor cost as

$$C_L = WT, \qquad (14)$$

since the labor cost is proportional to the construction time T for a specified workforce level W. Labor cost may be expressed in terms of workforce level using (13) as:

$$C_L = NK_o(K/K_o) \qquad (15)$$

The low density limit of (15) is from (11):

$$C_{Lo} = NK_o. \qquad (16)$$

In the low density limit one sees that total labor cost is independent of workforce level. The labor cost normalized on the basis of the low density limit is then (from (15), (16) and (11)):

$$C_L/C_{Lo} = K/K_o = \frac{(W/W_{cr})}{\tanh (W/W_{cr})} . \qquad (17)$$

Equation (17) indicates that the normalized total labor cost varies the same as the unit labor cost as would be expected for the same workforce level.

The indirect construction costs include (for the purposes of this study) all costs that are proportional to construction time duration. As mentioned in the Introduction, indirect costs are usually expressed as a fixed percentage of direct labor costs. Here indirect costs are expressed in a more general form that reflects the effect of variable workload. Indirect costs also reflect the degree of capital intensity of a given production facility. Indirect costs can be expressed in terms of an equivalent workforce level in a form similar to Equation (14):

$$C_I = W_{eq} T, \qquad (18)$$

where W_{eq} is the equivalent workforce level. The total cost (excluding material costs) can be written from (12), (14) and (18) as

$$C_T = (W_{eq} + W)\, T \qquad (19)$$

Fixed costs can be characterized by a dimensionless parameter β as follows:

$$\beta = W_{eq}/W_{cr} \qquad (20)$$

To illustrate the variation of costs with construction time T, consider first what happens if work density effects are ignored. In this case labor costs are constant, and equation (12) can be written using (18) as

$$C_T = W_{eq}T_o + C_{LO} \qquad (21)$$

where $C_{LO} = NK_o$ (from 16) is fixed and T_o is the zero density construction time. If total cost C_T is plotted against construction time, one sees that the costs increases linearly with time, with the minimum cost occuring at time $T_o = 0$. This result is not realistic because the minimum cost

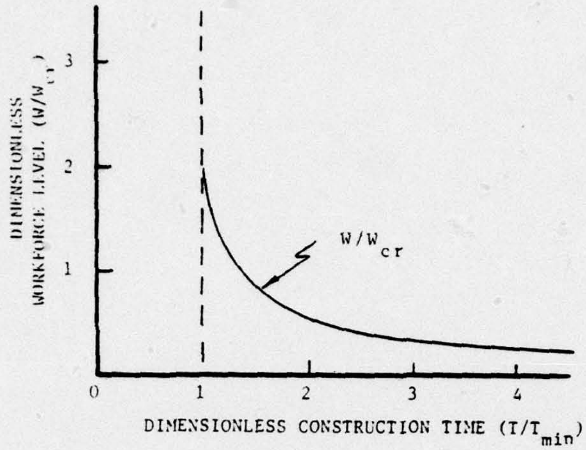


Figure 4. Dimensionless Workforce Level Versus Construction Time

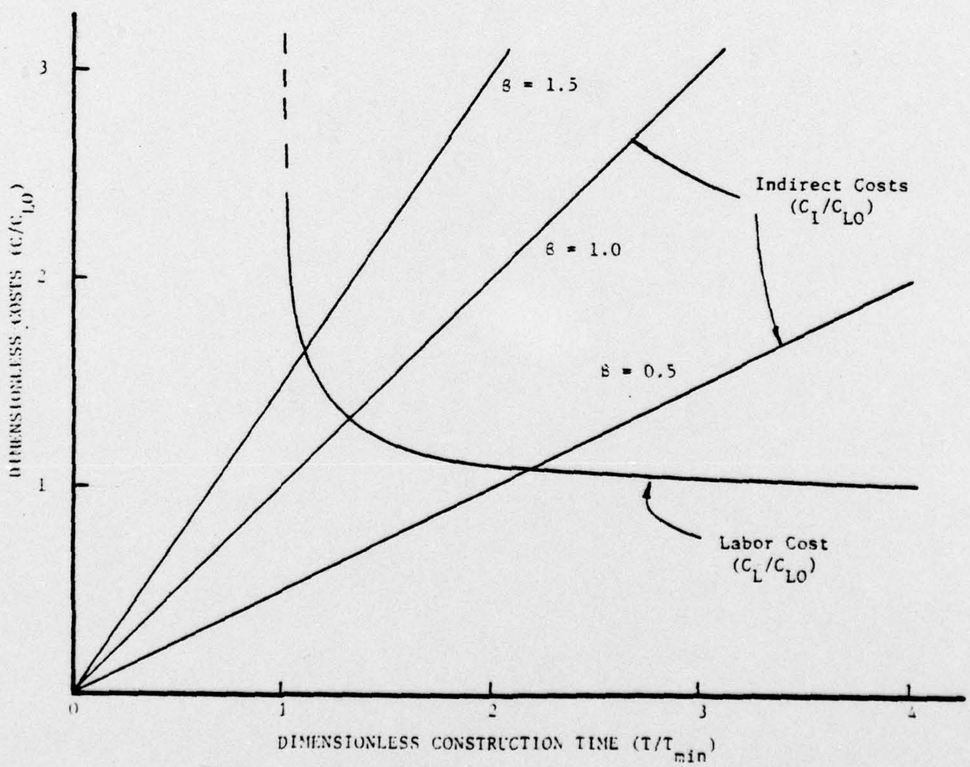


Figure 5. Dimensionless Costs Versus Construction Time

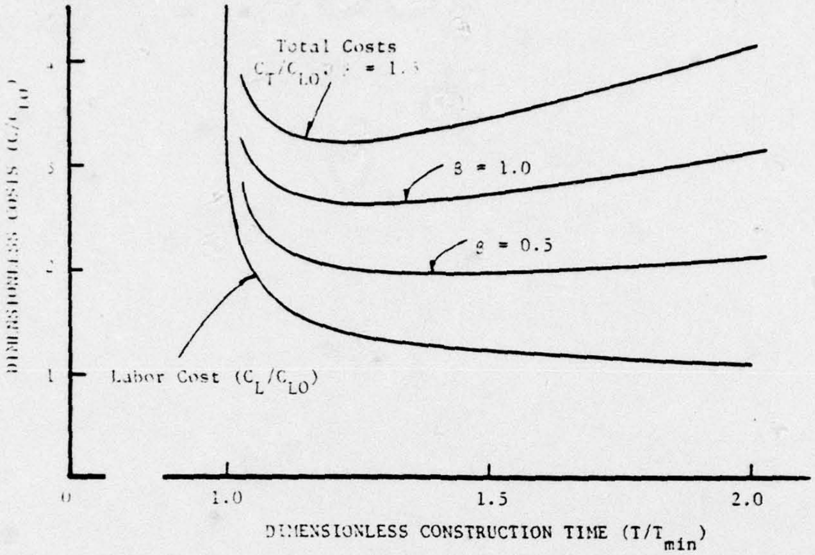


Figure 6. Dimensionless Costs Versus Construction Time

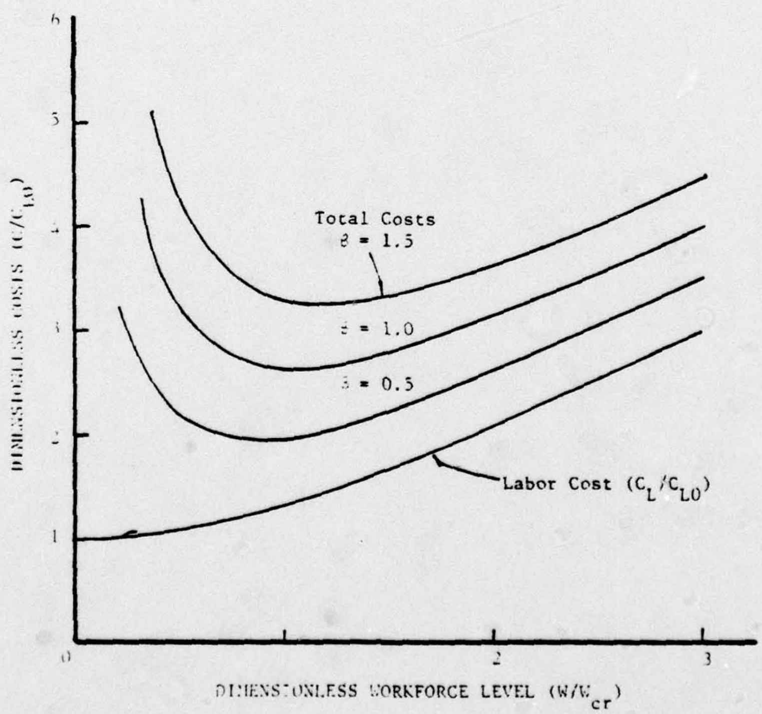


Figure 7. Dimensionless Costs Versus Workforce Level

can only be achieved with an infinitely large workforce. This can be seen from equation (14) after solving for W:

$$W = C_{LO}/T_o \qquad (22)$$

The resulting workforce curve is a hyperbola, with W going to infinity as T_o goes to zero. It is clear that the minimum cost point $T_o = 0$ cannot be achieved in practice because work density effects will decrease the productivity of the workforce, thus increasing labor costs.

To obtain a more realistic characterization of labor costs the effect of diminished productivity with increasing work density must be taken into account. For a production run of N units (ships) the production rate R and time T are related as follows:

$$N = RT \qquad (23)$$

Recall that the productivity reaches a maximum denoted R_∞ (see Figure 2). The time corresponding to maximum production rate must be the minimum denoted T_{min}. Since N is specified, one has from (23)

$$T_{min} = N/R_\infty. \qquad (24)$$

That is, the existence of a maximum production rate requires that a minimum construction time exists. The normalized or dimensionless construction time T/T_{min} can be obtained from (23) and (24):

$$T/T_{min} = (R/R_\infty)^{-1} \qquad (25)$$

From equation (3), the construction time is

$$T/T_{min} = 1/\tanh\,(W/W_{cr}) \qquad (26)$$

This equation relates the two independent variables, workforce level (W) and construction time (T). This relation (equation 26) is shown in graphical form in Figure 4. One sees that the workforce level is infinite at $T/T_{min} = 1$, i.e. at a finite construction time (T_{min}) instead of at zero time as was the case where work density effects were ignored.

Now returning to the cost equation (19) including work density effects, one has after normalization

$$C_T/(T_{min}W_{cr}) = (\beta + W/W_{cr})(T/T_{min}), \qquad (27)$$

where ($T_{min}W_{cr}$) is a normalizing cost. From (24), (16) and (5) one has:

$$T_{min}W_{cr} = NK_o = C_{LO} \qquad (28)$$

Equation (27) can be written using (28) as

$$C_T/C_{LO} = (\beta + W/W_{cr})(T/T_{min}) \qquad (29)$$

One may eliminate workforce level in (29) using (26) which gives

$$C_T/C_{LO} = \left\{\beta + \tanh^{-1}[(T/T_{min})^{-1}]\right\}(T/T_{min}), \qquad (30)$$

where $\tanh^{-1}$ denotes the inverse hyperbolic tangent. Separating the total cost (29) into its components gives

$$C_I/C_{LO} = \beta(T/T_{min}) \qquad (31)$$

and

$$C_L/C_{LO} = \{\tanh^{-1}[(T/T_{min})^{-1}]\}(T/T_{min}) \qquad (32)$$

The two components, C_L and C_I of the total cost C_T are plotted against construction time in Figure (5). One sees that labor cost is no longer constant as was the case when work density effects were ignored. Instead one sees that labor cost increases as construction time decreases, approaching infinity when the time equals the minimum time associated with the maximum production rate. Indirect costs, varying linearly with time, are shown for three values of β, the nondimensional indirect cost parameter. Total costs obtained by adding the components in Figure (5) are plotted in Figure (6) for three values of β. One sees that a minimum total cost exists for each value of β.

One may also express costs as a function of workforce level. This is a useful representation on a shipyard-wide level where one may want to compute the optimum workforce level needed to produce a given quantity (N) of identical ships. The corresponding optimum construction time can then be determined from Figure 4 or equation (26). Construction time can be eliminated in (29) by using (26), giving

$$C_T/C_{LO} = \frac{\beta + (W/W_{cr})}{\tanh\,(W/W_{cr})}, \qquad (33)$$

where indirect cost is

$$C_I/C_{LO} = \frac{\beta}{\tanh(W/W_{cr})} \qquad (34)$$

and labor cost is given by (17).

Total costs obtained by adding fixed and labor costs are shown in Figure 7 for three values of β. It is apparent that there exists an optimum workforce level for each value of β at which the construction cost is minimized. The minimum cost workforce level can be computed as a function of β by differentiating Equation (33) with respect to W/W_{cr} and setting the result equal to zero. The minimum cost construction time can then be computed from Equation (26).

RESULTS AND CONCLUSIONS

In the analysis described above a normalized production rate curve (Equation 3) characterizing work density effects was derived. Then the normalization parameters were expressed in terms of measurable production-related quantities. Costs were than analyzed using normalized construction time and normalized workforce level as independent variables. Costs were broken down into two groups: labor costs and indirect costs. The results are shown graphically in Figures 6 and 7. Total cost has a definite minimum as a result of the tradeoff between labor costs and indirect costs. The optimum construction time and workforce level

correspond to the minimum cost. The optimum point varies with the dimensionless parameter β, which characterizes (but is not the same as) overhead rate.

To aid in interpreting the results quantitatively, two Tables have been prepared. Table 1 shows the values of optimum (minimum cost) time and workforce level for the three values of β indicated in Figures 6 and 7. Overhead rate was computed at the optimum point, and is given as a percent of the labor costs. This permits a comparison with Mack-Forlist's data given in the Introduction.

Table 1. Minimum Cost Values for Time and Workforce Level and Corresponding Overhead Rate.

β	T/T_{min}	W/W_{cr}	Overhead Rate (Percent)
0.5	1.45	0.87	59
1.0	1.25	1.06	92
1.5	1.20	1.19	127

Mack-Forlist's data indicates an overhead rate of just under 100 percent, corresponding to the β = 1.0 curve if one assumes the yard is operating at or near its optimum minimum cost point. That is, a β value of 1.0 is typical for U.S. yards according to Mack-Forlist's study. It should be noted that the optimum construction time is 25 percent above the minimum and the optimum workforce is slightly over the critical workforce level. This means that work density effects are quite strong: Figure 3 indicates the labor cost is 33 percent above the low density limiting cost.

The curves in Figures 6 and 7 were used to compute the percentage change in construction time and workforce for a cost increase of ten percent over the minimum. (Recall that cost here excludes material cost.) The results appear in Table 2.

Consider the β = 1.0 (92 percent overhead) case. The increase in cost can be achieved by either accelerating or slowing construction. The first two columns slow the results for expediting the work. From Table 2, the ten percent cost increase will reduce construction time by 14 percent, but will require a 31 percent increase in production workers. Alternatively, the construction time can be increased by 31 percent with a ten percent increase in costs. The resulting workforce reduction in this case is 40 percent. It is apparent from the Table that it is more expensive to expedite work than it is to extend it. This is because labor costs blow up as the minimum construction time is approached. (See Figure 5.)

In addition, note that as β (and thus overhead rate) increases the optimum minimum cost point gets closer to T_{min}. This means that yards with higher overhead rates reflecting higher capital intensity tend to be less flexible in adjusting to changes in workload. That is, the incremental costs are higher for the same change in construction time. This effect will be alleviated to some extent by the lower unit costs that should result from a higher degree of automation. Recall that costs have been normalized using low density labor costs, which should decrease as automation (capital intensity) increases.

Note that by assuming that a given yard is operating at a particular time at its minimum cost point, a particular value of β can be assigned since the overhead rate is known (Table 1). This then determines the yard's cost curve as a function of workforce level or construction time (Figures 6 and 7). Then the workforce can be determined relative to the critical workforce from Table 1 as the ratio (W/W_{cr}). The following identity can be developed using Equation (7):

$$W/W_{cr} = (W/A)/(W_{cr}/A) = (W/A)/\alpha$$

Since (W/W_{cr}) and the total work area of the yard are known, the yard's critical work density α can be found. Similarly, the low density labor cost K_o can be determined from Figure 3 since W/W_{cr} and labor cost K are known. That is, one may work backward from the assumed optimum point to obtain quantitative values for the parameters needed in the analysis.

The alternative procedure is to start with a production curve, i.e., production rate versus workforce level. This curve can be curve-fit to Equation (3), the normalized production curve provided the data cover a sufficient range to include the dropoff in output due to work density effects. Once the production curve has been established the other parameters are relatively easy to obtain from historical data. Obtaining the production curve from historical data is especially difficult because the data is "contaminated" by numerous effects which have not been taken into account in this study. These effects include:

1. Varying types of ships (Nonuniformity of items being constructed)
2. Inflation
3. Learning
4. Changes in yard's production facilities/processes
5. Variation of workforce over construction period.

Table 2. Increments in Construction Time and Workforce Level for a Ten Percent Increase in Costs.

β/(Percent Overhead)	Percent Reduction in Constr. Time	Percent Increase in Production Workers	Percent Increase in Constr. Time	Percent Reduction in Production Workforce
0.5/(59)	22	47	47	39
1.0/(92)	14	31	31	40
1.5/(127)	13	32	32	45

Further work is planned to verify the model presented here using historical data after compensating for the factors listed above. This phase will require extensive computer analysis.

ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research as part of their Acquisition Research Program under contract number N00014-78-C-0411. The inspiring discussions with Dr. Franz A. P. Frisch of the Defense Systems Management College are gratefully acknowledged. These discussions resulted in helpful suggestions and constructive criticism of the work presented here.

REFERENCES

1. Frisch, F. A. P., Production and Construction, A Comparison of Concepts in Shipbuilding and Other Industries, Prepared for the 5th Annual DOD Procurement Research Conference, Nov. 17 - 18, 1976, U.S. Department of the Navy.

2. Benford, H., General Cargo Ship Economics and Design, The University of Michigan Department of Naval Architecture and Marine Engineering, Aug. 1962.

3. Mack-Forlist, D. M., The Conversion of Shipbuilding from Military to Civilian Markets, Praeger, New York, 1970.

APPENDIX B

A DIAGNOSIS OF THE WORKLOAD VARIATION PROBLEM IN SHIPBUILDING

William Robert Terry *

Forrest Green *

Allen H. Magnuson **

and

Dennis L. Price *

* Department of Industrial Engineering and Operations Research

** Department of Aerospace and Ocean Engineering

Virginia Polytechnic Institute and State University

Blacksburg, Virginia 24061

PREFACE

The Industrial Engineering and Operations Research Department's activities were divided into three phases. The first phase, which is reported in this document was designed to identify specific problems for further analysis. This analysis revealed the need for the following:

(1) a system for analyzing how variations in shipyard workloads affect shipbuilding cost;

(2) a shipyard planning system which could be utilized by shipyards to minimize the cost of adjusting to workload variations.

Phase 2 focused on developing the framework of a system for developing transfer function models which can be used to develop the difference equations which describe how variations in shipyard workloads affect shipbuilding cost. Phase 3 focused on developing the framework of a shipyard planning system which shipyards could use to minimize the cost of adjusting to workload variations.

OBJECTIVES

The purpose of this phase was to determine the relative importance of the problems created by workload variation and to identify specific problems for further analysis in the second and third phases. This research has focused on two objectives. The first objective was to develop the framework of a system for analyzing how variations in shipyard workloads affects shipbuilding cost. Such analyses could be used by those responsible for establishing Navy shipbuilding budgets to analyze how alternative funding programs influence both procurement cost and mobilization potential. The second objective was to develop the framework for a shipyard planning system. Such a system could be utilized by shipyards to minimize the cost of adjusting to workload variations.

LITERATURE REVIEW AND SHIPYARD VISITS

A variety of techniques were utilized to acquire this information. Discussions with personnel in the Naval Sea Systems Command, the Office of Naval Research, the Maritime Administration, the Census Bureau, and the Bureau of Labor Statistics uncovered a large number of potentially relevant documents (see Appendix A). These documents were reviewed for relevance and a classification system (see Appendix B) was developed to facilitate locating potentially useful information. The following shipyards were also visited:

(1) Norfolk Naval Shipyard; Portsmouth, Virginia; December 21, 1978

(2) Norfolk Shipbuilding and Drydock Company; Norfolk, Virginia; March 20, 1979

(3) Newport News Shipbuilding and Drydock Company; Newport News, Virginia; March 20, 1979

(4) Todd Shipbuilding; Seattle, Washington; February 2, 1979.

The documents reviewed and the confidential discussions with shipyard executives during the visits revealed that the following were potential causes of low productivity:

Unavailability of labor at the time needed (low labor progress);

Insufficient skilled personnel (low manning level);

Improper order of sequence of assigned labor;

Interference by different crafts (incompatibility);

Too many personnel working at one time (work density); and

Accelerated schedules (work speedup).

STRUCTURED TELEPHONE INTERVIEWS

In order to determine the extent to which these potential causes actually occurred, a structured interview questionnaire (see Appendix C) was designed to be administered by telephone to executives, industrial engineers, and production or construction scheduling managers at various shipyards. The shipyards were chosen so that a representative sample of large and small shipyards in several Naval districts would be included in the survey.

Twenty-one shipyards were included in the interviews (see Appendix D). All but two had facilities to construct ships or barges larger than 300 feet, and all but four had employment of over 1,000 personnel. Eleven of the shipyards were categorized as "majors"; and seven Naval districts were included overall. Seven of the shipyards are currently constructing Navy ships, and all but two were involved in commercial ship construction.

ANALYSIS OF STRUCTURED TELEPHONE INTERVIEWS

The results of these structured telephone interviews are summarized in Table I. The entries in this table indicate the number of shipyards surveyed that ranked the causes of variation in productivity in the top three. Shipyards were classified with respect to size and whether or not they built Navy ships.

The most striking feature of this table is the high number of responses pertaining to low labor progress and low manning level at major shipyards, particularly those performing Navy and merchant ship construction. This suggests the importance of labor and craft availability at many shipyards constructing merchant and Navy ships.

Intermediate size shipyards were more likely to indicate problems related to improper order of assigned personnel, craft interference, and work density as the major causes of variation in productivity. Smaller shipyards selected low manning levels, craft incompatibility, work density and accelerated schedules as major causes of productivity variation. In the category cited as "other causes", a number of shipyards reported material delays and shortages to be of major concern. Each of these items is discussed in more detail below.

Taken together, it is evident that unavailability of labor and insufficient skilled personnel are regarded as major causes of variation in productivity by shipyard executives. This finding corresponds with a 1977, Department of Defense report which stated that the majority of all completion delays were due to low labor progress resulting from inadequate manning by the shipbuilders (Department of Defense, 1977).

TABLE I

Primary* Causes of Variation in Productivity Reported by Shipbuilding Executives in Twenty-One Private U.S. Shipyards from January through March of 1979

Shipyard Size		Major		Intermediate	Small	
Causes of Variation in Productivity	Builders of Merchant Ships	Builders of Navy Ships	Navy and Merchant Ships	Builders of Commercial Ships	Commercial Ships and Boats	Overall Totals
Craft:						
Low Labor Progress	3	1	6	2	1	14
Low Manning Level	2	1	6	1	3	13
Improper Order of Tasks	1		2	4	1	8
Craft Incompatibility	1		2	4	3	10
Work Density	2		1	2	3	8
Accelerated Schedules	2		1	2	3	8
Other:						
Delayed Materials	1	1	4	3	1	10
Improper Work Breakdown			1	1		2
Engineering Changes			2			2
Facilities and Weather	2			1		3
Number of Shipyards	4	1	6	6	4	21

*Respondents were asked to select the three foremost causes of variability from the list in the first column.

The survey revealed that intercraft interference and intracraft work density are significant problems as well. Several managers pointed out that these conditions can be brought about by accelerated schedules and improper assignement of personnel even though shipyard manning is at a relatively low level. Some find it necessary to stagger personnel in shifts in order to reduce craft interference. (This is particularly true on smaller vessels, such as submarines.)

Intercraft interference and work density are most often experienced in the engineering spaces aboard ship and in some of the more specialized compartments during outfitting. Navy ships, with their complex electronics and weapons systems, often experience this concentrated activity. The crafts which were found to be least compatible due to the nature of their work are painters and finishers. Also, welders can have no personnel working beneath them, and forced air blowers often restrict the amount of work other crafts can perform at the same time.

The problem of craft interference and work density may be related to a problem cited by shipyard workers in a MarAd* study of nearly 1,300 employees representing ten shipyards. The most common spontaneous complaint among production workers which is related to working conditions concerned inadequate scheduling, planning, coordinating, and communicating between crafts, shifts and various working groups (Muench, 1976).

The survey also revealed a problem which appears to be growing in dimension at many of the shipyards. A number of managers listed material shortages and delays as being among the top three causes of variation in productivity even though late material was not listed as a specific item

---

* Maritime Administration, Washington, D. C.

on the questionnaire. Late material deliveries were discussed in a 1977 Department of Defense report, but no increase in lead time trends was apparent at the time (Department of Defense, 1977). Subsequent reports may produce different results. A number of shipyard managers believe the problem to be getting worse.

Another outcome of the shipyard survey summarized in Table II is an illustration of the degree of activity in ship construction and the stages at which the greatest concentration of personnel is likely to occur. For most ships, this occurs during machine installation and outfitting. A notable exception is the construction of tankers in which the most activity occurs during the steel fabrication phase. This is particularly true of shipyards using modular construction or block techniques which bring needed sections of the hull together as they are fabricated and joined.

NEED FOR SHIPYARD PLANNING SYSTEM

The results of the above survey clearly indicate that an effective shipyard planning system must take the following into account:

(1) Labor availability

(2) Material availability

(3) Craft incompatibility and interference.

Failure to do so often results in the scenario described by Chirillo as "the falling domino effect" illustrated in Figure 1. In this scenario, low labor progress on precedent activities, delayed materials, or workflow disruptions (caused by inclement weather, strikes, etc.) bring about a period of forced idleness and low labor progress which results in an

TABLE II

Stages of Ship Construction Experiencing the Most Activity by Ship Type

(with Non-Traditional Construction Techniques Noted)

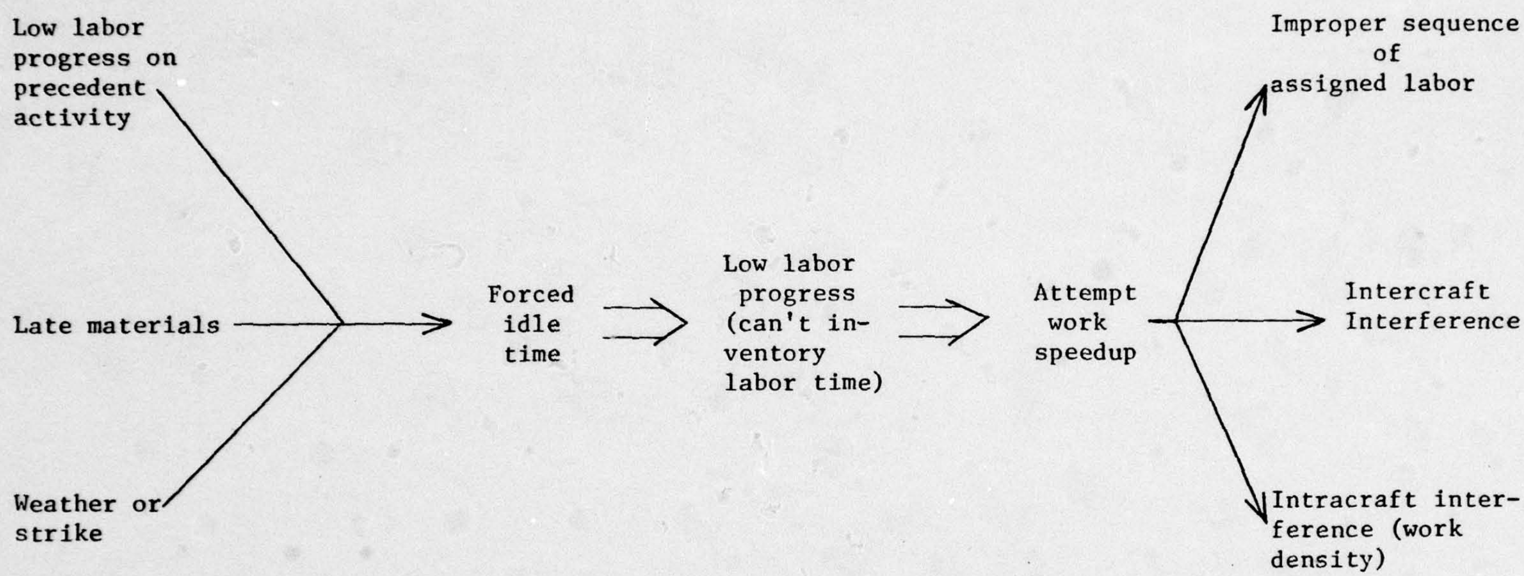
Responses of 21 Shipyards Constructing Eight Different Ship Types (Total 41 Responses)

Type of Ship	Early Stages (Up to 33% Complete)	Mid-Construction (34%-67% Complete)	Final Stages (68%-100% Complete)
Navy Combatant			4
Navy Non-Combatant		1+	1* 2
Bulk (ore) Carrier		1	2
Container Vessel		2	3
Tankers, LNG[1]	1* 1+ 1	1* 1+ 4	4
Freighters, Cargo Ships		1	2
Boats		1*	5
Barges	1		2
Total	4	12	25

* Modular construction

\+ Block construction

[1] LNG - Liquified Natural Gas Carrier



Source: Cdr. Louis D. Chirillo, USN (Ret.), R & D Program Manager, Seattle Division, Todd Shipyards Corporation.

Figure 1. <u>The "Falling Domino Effect" of Construction Delays and Disruptions in Shipbuilding</u>

attempted work speedup during a later period. When the schedule is accelerated to make up for lost time and avoid late penalties, inefficiencies occur due to improper sequence of assigned labor, interference between crafts, and interference within crafts as too many personnel require access to the same space. The review of documents and discussions also revealed a number of statements which describe, in qualitative terms, how variations over time, in the demand for ships, adversely impacts cost and productivity.

The following statements were found in a report prepared for the Maritime Administration.

> Introduction of new or improved management procedures [should be encouraged], particularly those which improve ship construction scheduling and thus minimize the present queueing problems that occur when certain shipyard occupations are used intensely for some time, only to stand idle later. The lessening of insecurity about this layoff/rehire pattern could attract more workers. (Mark Battle Associates, Inc., 1974, p. 8)
>
> Generally, the rate of voluntary quits and discharges increases significantly during shipyard employment expansion. (Mark Battle Associates, Inc., 1974, p. 45)
>
> Higher turnover rates were reported by shipyard officials to be highly correlated with manpower expansion in the shipyards. (Mark Battle Associates, Inc., 1974, p. 55)

NEED FOR MODEL TO PREDICT HOW VARIATIONS IN DEMAND AFFECT SHIPBUILDING COST

In addition to the above, Mr. E. Karlson of the Maritime Administration, provided the following statement:

> "Shipyard productivity is difficult to measure because of the uniqueness, sophistication and diversity of vessels being constructed. There are, however, several conclusions of a qualitative nature that can be stated with respect to productivity associated with a declining orderbook.
>
> 1. When employees know that they are working themselves out of a job, there is certainly no incentive to either maintain their level of productivity or to improve it. This is a known fact to shipyard management but difficult to document.

2. Ongoing shipyard overhead costs will be distributed over a smaller product base. This adversely affects the shipyard's capability to economically compete for new work.

3. Lower paid employees with lower seniority will be separated first during a manpower reduction. This will result in an increase in the average wage rate for those employees retained. Such an increase in average wage will have an adverse impact on the shipyard's capability to economically compete for new work.

4. A declining orderbook will result in under utilization of existing capacity adversely impacting on efficient production control.

5. There will be no incentive for capital investment to further improve productivity when a shipyard's orderbook is declining. In shipyards where recent large scale private capital investments were triggered by the Merchant Marine Act of 1970, increased productivity benefits have directly accrued to the government; that is to subsequent Navy shipbuilding programs in those yards.

6. Even when a declining orderbook is reversed and new contracts are received, there will be reduced productivity associated with new hires until they are fully trained and capable at their jobs. The employee recall success rate in shipyards is about 50 percent. Reduced productivity must therefore be recognized for the other 50 percent until they are fully capable employees.

7. There will be direct costs of training new employees during a recovery period." (Karlson, 1979)

The above statements suggests the impact of a change in the demand for ships on productivity and cost is likely to be in a number of time periods as opposed to being concentrated in a single period. Time is required to recruit and train the new workers needed to meet an increased demand. The tendency of workers to slow down during times of low demand is likely to persist for some time after demand increases. These statements also suggests that both delayed and anticipatory reactions could occur. Memories

of past layoffs are likely to make potential workers reluctant to accept employment with a shipyard. This can cause the workforce expansion plans to be delayed. Memories of past layoffs can motivate shipyard workers to voluntarily quit to accept more secure jobs if they suspect that the level of demand is likely to fall in the future. The tendency for the impact to be felt in more than one time period combined with the possibilities of both delayed and anticipatory reactions strongly suggests that it will be necessary to use either differential equations or difference equations to analyze how changes over time in the demand for ships impacts productivity and cost.

REFERENCES

1. Department of Defense. Annual Report on the Status of Shipbuilding and Ship Repair Industry of the United States - 1977. Coordinator of shipbuilding, Conversion and Repair, Office of Maritime Affairs, Naval Sea Systems Command, Washington, D. C., 1977.

2. Karlson, E., personal communication, 1979.

3. Mark Battle Associates, Inc., "Shipbuilding Manpower Study: Executive Summary, March, 1974.

4. Muench, George A. Study for the Improvement of Motivation in the Shipbuilding Industry, Phase I, Prepared for the Maritime Administration National Shipbuilding Research Program by Dr. George A. Muench and Associates, San Jose State University, San Jose, California, June, 1976.

APPENDIX A

SOURCES AND REFERENCES ON SHIPBUILDING

1. Annual Report on the Status of the Shipbuilding and Ship Repair Industry of the United States: 1977, Coordinator of Shipbuilding, Conversion, and Repair, Department of Defense.*

Section	Pages	Topic
A	1-1 to 1-66	Status of shipbuilding industry
B	2-1 to 2-5	Research and reports
C	2-5 to 2-19	Shipbuilding claims
D	2-19 to 2-23	Navy/industry relations
E	2-23 to 2-25	Cost estimating
F	2-25 to 2-36	Delay factors
G	2-36 to 2-43	Cost scheduling and miscellaneous
H	3-1 to 3-4	Shipbuilding labor, history
I	3-4 to 3-13	Training
J	3-13 to 3-18	Labor availability
K	3-19 to 3-33	Manpower fluctuations, wages, strikes, etc.
L	4-1 to 4-18	World shipbuilding

2. Modern Ship Design by Thomas C. Gillmer, Naval Institute Press, Annapolis, Maryland, 1975.

Section	Pages	Topic
A	185 to 191	Shipbuilding methods, Europe
B	192 to 203	Shipbuilding methods, U.S.

3. Ship Design and Construction, Edited by Amelio M. D/Arcongelo, Society of Naval Architects and Marine Engineers, New York, 1969.

Section	Pages	Topic
A	456 to 360	Planning and scheduling
B	461 to 462	Use of models
C	463 to 469	Lofting, steel ordering and processing

---

* Annual Report of the Status of the Shipbuilding and Ship Repair Industry of the United States: 1976. (Report of the previous year, similar to the above, with data pertaining to the status as of 1976).

D	469 to 476	Steel fabrication and erection
E	476 to 477	Blocking, storing, and staging
F	478	Machinery installation
G	479 to 480	Outfitting

4. Department of Defense Instruction, Number 7000.10, Contract Cost Performance, Funds Status Cost/Schedule Status Reports, August 6, 1974.

5. Acquisition Management, Cost Performance Reporting and Baseline Management, Office of the Assistant Secretary of Defense (Comptroller).

6. Acquisition Management, Cost/Schedule Status Report (C/SSR), Office of the Assistant Secretary of Defense (Comptroller).

7. Employment and Earnings, February 1978, U.S. Department of Labor, Bureau of Labor Statistics, Vol. 25, No. 2.

8. Effect of Work Density on Productivity in the Overload Condition by Allen H. Magnuson, August 1978.

9. The Tradeoff Between Learning and Inflation in Shipbuilding, by Dr. F. A. P. Frisch and Charles Todd, Naval Sea Systems Command, Department of the Navy, August 1977.

Section	Pages	Topics
A	19 to 46	Inflation-learning program model
B	47 to 59	Inflation-learning actual program

10. Production and Construction: A Comparison of Concepts in Shipbuilding and Other Industries by Dr. F. A. P. Frisch, Prepared for the 5th Annual DOD Procurement Research Conference, November 17-18, 1976.

Section	Pages	Topics
A	17 to 44	Production and construction, overview
B	45 to 71	Behavior of products and production
C	72 to 78	Cost determination in production and construction
D	79 to 92	Management of construction

11. General Cargo Ship Economics and Design by H. Benford, University of Michigan, July 1962.

Section	Pages	Topics
A	61 to 70	Weights, estimating
B	71 to 85	Building costs

12. "Weight, Cost, and Design Characteristics of Tankers and Dry-Cargo Ships" by R. P. Johnson and H. P. Rumble, Marine Technology, April 1965.

13. Naval Sea Systems Command Monthly Progress Report for Shipbuilding and Conversion, U.S. Department of the Navy, 1 September 1978.

14. Lecture Notes on Industrial Economy, by Dr. Franz A. P. Frisch, Virginia Polytechnic Institute and State University, 1977, Note Nos. 215-224.

15. Notes: Results of Analysis "Loss of Learning", A re-analysis of Litton's Report showing loss of learning due to interruptions of two series of ships, author and date unknown.

16. Status of the Navy Shipbuilding and Conversion Program, U.S. Dept. of the Navy, 15 August, 1978.

17. Draft: Organization of Acquisition Research Topics - Navy, by Dr. Franz A. P. Frisch, Naval Sea Systems Command, 20 January 1978.

18. Letter: ORI Inc., Silver Spring, Maryland, from Jonathan A. Sisson to Dr. Allen Magnuson, VPI & SU, 25 September 1978.

19. ONR - Manhours and Cost Record, Contracts Completed Since 1951, Industrial Engineering Department, 5-24-61.

20. Cost/Schedule Control Systems Criteria, Joint Implementation Guide, Departments of the Air Force, the Army, the Navy, and the Defense Supply Agency, 1 October 1976.

21. ONR Project - Field Visit and Interview, by Forrest B. Green, GRA, VPI & SU, conducted at NOrfolk Naval Shipyard, Portsmouth, Virginia, 21 December 1978.

22. Economics, 3rd ed., by Lloyd G. Reynolds, publisher Richard D. Irwin, Inc., Homewood, Illinois, 1969 -- Chapter 20, "Factor Markets and Factor Prices".

23. Ideal Labor Progress Curves: New Construction and Conversions, NAVSEA, provided by Harold Paul, summer, 1978.

24. Shipyard Detail Information (Chart), NAVSEA, provided by Harold Paul, summer, 1978.

25. Manhours per Ton by Ship/Type (Table), NAVSEA, provided by Harold Paul, summer, 1978.

26. Gantt Charts and PERT Networks, Norfolk Naval Shipyard.

27. Network Analysis and its Application to Shipbuilding, by Chambers et al., Paper presented at the Royal Institute of Naval ARchitects meeting, London, England, March 23, 1965.

28. Principal Shipbuilding and Repair Facilities of the United States, DOD and DOC, Office of the Coordinator for Ship Repair and Conversion, June 1, 1975.

29. 1977 Report on Survey of U.S. Shipbuilding and Repair Facilities, DOC, MARAD, Office of Ship Construction, Division of Production, December 1977.

30. Cost Report Summary, Chesapeake Corporation of Virginia, West Point, Virginia, October 20, 1977.

31. Labor and Material Cost Report, prepared by the Rust Engineering Company, A five-part contract report compilation prepared for the Chesapeake Corporation of Virginia, October 18, 1977.

32. Cost/Schedule Control Systems Criteria (C/SCSC) Joint Surveillance Guide, Naval Material Command Pamphlet, NAVMAT P5243, July 1, 1974.

33. A Statistical Summary of Shipbuilding Under the U.S. Maritime Commission During W.W.II, by Gerald J. Fisher, Historical Reports, No. 2, 1949.

Section	Pages	Topic
A	17 to 31	Programs planned and accomplished
B	32 to 56	Total and regional shipbuilding
C	57 to 79	Shipbuilding by individual yards
D	80 to 89	Speed of construction
E	90 to 106	Facilities
F	107 to 113	Steel
G	114 to 147	Labor
H	148 to 164	Productivity and costs

34. Military Standard Production Management, MIL-STD-1528 (USAF), August 1, 1972.

35. Department of Defense Instruction, Number 7000.2, June 10, 1977, Performance Measurement for Selected Acquisitions.

36. Military Standard Work Breakdown Structures for Defense Material Items, MIL-STD-881A, April 28, 1975.

37. Naval Analysis Programs: Description of Study Areas, FY 77-79, December 1975.

38. Interview with Norman Blumberg, Nuclear Test Engineer, Norfolk Naval Shipyard, Portsmouth, Virginia, by F. B. Green, September 8, 1978.

39. Confidential Interview with Mr. William Nelson, Fiance Officer, Major East-Coast Construction Firm, by F. B. Green, September 15, 1978.

40. Lecture Notes on "Industrial Economy" by Dr. Franz A. P. Frisch, VPI & SU, 1977, Note Nos. 163-190.

41. Lecture Notes on "Industrial Economy" by Dr. Franz A. P. Frisch, VPI & SU, 1977, Note Nos. 121-162.

42. An Overview of the Shipbuilding Labor Market, by Sheldon E. Haber and John C. Martin, George Washington University, Institute for Management Science and Engineering, Serial T-331, March 24, 1976.

43. The Conglomerate Firm, edited by Arnold C. Hax and Zenon S. Zannetos, Technical Report No. 5, Sloan School of Management, MIT, June 1978.

Section	Pages	Topic
A	76 to 104	Conglomerates in the shipbuilding industry
B	185 to 209	The shipbuilding company in a multi-divisional corporate environment

44. Annual Report of the Maritime Administration [not on board].

45. Shipyard Employment Report, monthly, Office of Maritime Manpower, Maritime Administration [not on board].

46. Private Shipbuilding and Conversion Shipyards - Facilities Data, prepared by NAVSEA 075 (no date, probably 1975), loose bound.

Section	Part	Topic
A	I	Construction and conversion eligibility of yards
B	II	Size, capacity, and facilities of shipyards

47. Development and Application of a Computer Controlled Ship's Frame Bender in the Automated Shipyard, by Acton et al., paper presented at the Annual Meeting of the Society of Naval Architects and Marine Engineers, November 16-18, 1978.

48. Ways to Increase Shipbuilding Productivity, Report to the Congress by the Comptroller General of the United States, September 23, 1976.

49. Brevu - Bremer Vulcan, Schiffbau und Maschinefabrik (Shipbuilders and Marine Engin-ers), brochure provided by Bemer Vulcan, Weserstrabe, Germany, 1978.

50. The Profitability of the U.S. Shipbuilding Industry, 1947-1976 by Edward M. Kaitz, report prepared under Acquisition R&D Program of the Office of Naval Research, June 20, 1978.

51. Productivity, extracted from internal report prepared at MARAD in December 1977, provided by E. Karlson.

52. Proceedings for Shipbuilding/Industrial Production Engineering Workshop, U.S. Dept. of Commerce, Maritime Administration, in cooperation with Bath Iron Works Corporation, prepared by American Institute of Industrial Engineers, Atlanta, Georgia, February 21-24, 1978.

Section	Pages	Topic
A	II-1-6	Production planning, scheduling and control
B	II-7-12	Methods and standards
C	C-1-19	Productivity
D	D-1-21	Inspection guidelines, hull

53. Aspects of the National Shipbuilding Research Program which Impact on Owners, Designers, Regulators, and Suppliers, by L. D. Chirillo, R & D Program Manager, Todd Shipyards Corporation, Seattle Division, 1 October 1977.

54. Outfitting and Production Aids by Lou Chirillo and others, March 7, 1979.

55. Comment and Discussion by Cdr. L. D. Chirillo on two articles: "The Future of the Navy," U.S. Naval Institute Proceedings, June 1977, pp. 83-84; "Attack Submarine Development-Recent Trends and Projected Needs," U.S. Naval Institute Proceedings, November 1978.

56. Questionnaire: National Shipbuilding Research Program Product Oriented Work Breakdown Structure by L. D. Chirillo, R & D Program Manager, Todd Pacific Shipyards Corporation, Seattle, Wash., December 1, 1978.

57. "Industrial Dynamics: A Major Breakthrough for Decision Makers," Harvard Business Review, July-August, 1958.

58. Study no. T-383, The United States Shipbuilding Labor Market 1960-1970, extract: author unknown.

59. The National Shipbuilding Research Program, "Study for the Improvement of Motivation in the Shipbuilding Industry," by the U.S. Dept. of Commerce Maritime Administration in cooperation with Newport News Shipbuilding and Dry Dock Company, June 1976.

60. Study no. 163, Shipbuilding Manpower Study Executive Summary, by Mark Battle Associates, Inc., Washington, D.C., March 1974.

61. Study no. 163, Shipbuilding Manpower Study, by Mark Battle Associates, Inc., March 1974.

62. Study no. 163, Shipbuilding Manpower Study Appendices, by Mark Battle Associates, Inc., March 1974.

63. Rational Approaches to Raising Productivity, by Mitchell Fein, PE Consultant, WM & ME Monograph Series No. 5, 1974.

64. Motivation for Work, by Mitchell Fein, WM & ME Monograph Series No. 4, 1974.

65. Improved Planning and Production Control, Prepared by Bath Iron Works Corporation under Marad Task 0-2 of the Ship Producibility Research Program, August 1977.

66. A Manual on Planning and Production Control for Shipyard Use, Prepared by Corporate-Tech Planning, Inc. for Bath Iron Works Corporation under MarAd Task 0-2 of the Ship Producibility Research Program, September 1978.

67. Wage Incentive Plans, by Mitchell Fein, Publication No. 2, American Institute of Industrial Engineers, May 5, 1970.

68. Potential Ship Structure Misalignment Tolerance Guidelines, Final Technical Report (Draft), Part No. 1 of Standard Structural Arrangements Task S-11 of Ship Producibility Program, General Dynamics, Quincy Shipbuilding Division.

69. Gert Modeling and Simulation: Fundamentals and Applications, by L. Moore and E. Clayton, New York: Petrocelli-Charter, 1976.

70. Modeling and Analysis Using A-GERT Networks, by A.A.B. Pritsker, New York: Halsted Press, 1977.

71. The GASP IV Simulation Language, by A. A. B. Pritsker. New York: Wiley-Interscience, 1974.

APPENDIX B

CLASSIFICATION SYSTEM FOR SOURCES AND REFERENCES ON SHIPBUILDING

I. Hull Fabrication

	Source*
Block building of ships	2A p. 187
Hull construction, up-side-down, Avondale	2B p. 193, 199
Automated plate handling, Newport News	2B p. 195
Steel fabrication and erection	3D
Blocking, shoring, and staging	3E
Shipyard: steel production schemata	10D p. 89
Hull weights	11A pp. 61-67
Hull costs	11B pp. 71-72
Weight, cost, and design characteristics of tankers	12
Hull structure - definition	36 p. 77
Computer controlled ships frame bender	47
Inspection and dimensional guidelines	52D
Weld testing, joining, use of composite plastics, and piping	53
Potential ship structure misalignment tolerance	68

* See Appendix A for source identification.

INDEX

II. Propulsion Machinery

INDEX

INDEX

INDEX

V. Shipbuilding Labor (continued)

	Source
Manpower distribution - shifts and incompatability	40 Notes 186-190
The shipbuilding labor market	42
*Shipyard employment data - 27 yards	45
Equivalent men per day - Newport News Shipbuilding and Dry Dock Company	46B
*Number of persons employed - private shipyards	46B
*Current employment - 12 major shipyards	43A pp. 91-94
Labor resources - improving shipbuilding productivity	48 pp. 7-8
Declining orders - employees working themselves out of job	51
Effects of overtime - absentee rate, general morale, work quality	52A, II - 3
Need to improve work force motivation and morale	52A II-4 II-6
U. S. shipbuilding labor market 1960-1970	58
Improvement of motivation	59
Shipbuilding manpower study - shipyard employment statistics, manpower assessment, special studies, and competitive environment	60, 61
Shipbuilding manpower statistics - by trade, region, shipyard, etc.	62
Motivation to work - factors affecting motivation	64

INDEX

INDEX

VII. Variation in Productivity

INDEX

INDEX

INDEX

INDEX

INDEX

XI. Networks

APPENDIX C

STRUCTURED INTERVIEW QUESTIONNAIRE

SHIPYARD INTERVIEW QUESTIONNAIRE

Introduction:

My name is ______________________ and I am calling from the Industrial Engineering and Operations Research Department of Virginia Polytechnic Institute. We are currently engaged in a research project sponsored by the Office of Naval Research entitled "Analysis of the Cost of Variable Workloads on Shipbuilding". The project is part of a basic research program in the area of ship acquisition.

I have been asked to contact people at various shipyards in order to gather information on some of the areas in which our research will be directed. I have been assured that all data will be treated confidentiality, and no names or titles will be used without permission. If you wish to verify authorization for this project, I can give you the ONR Project Number.

Project Number is 230-11-022-106-352965-1.

Questions:

In your position, what phase of ship construction are you most concerned with?

( ) Hull fabrication

( ) Propulsion machinery installation

( ) Auxilliary machinery installation

( ) Outfitting

( ) Other ____________________

What trades are directly involved in the type of work you supervise?

____

____

____

____

____

At what stage of ship construction do you experience the most activity?

( ) Pre-construction, design

( ) Early construction (up to 33% complete)

( ) Mid-construction (33% to 67% complete)

( ) Final stages (67% to 100% complete)

( ) Post-construction, retro-fitting and overhaul.

Which area of the shipyard (or shipboard space or compartment) involves the most activity that you experience? (Where in the shipyard is the most activity experienced?)

____

____

____

Which activity or group of activities in that area or space involve the highest concentration of personnel?

____

____

____

____

What are the trades involved in this activity or group of activities?

____

____

____

____

We recognize that most shipyards do a very good job of meeting schedules and filling orders; but variations in productivity do occur, and we are trying to focus our attention on the reasons for these variations. If you could jot these things down, I am going to give you a list of items which may cause variation in job completion time and ask you to rate the top three items in order of importance:

_____ Unavailability of labor at the time needed (low labor progress)

_____ Insufficient skilled personnel (low manning level)

_____ Improper order or sequence of assigned labor

_____ Interference by different crafts (incompatibility)

_____ Too many personnel working at one time (work density)

_____ Accelerated schedules (work speedup)

_____ Other causes ____________________________________

____

____

(Ask the following questions if interference or work density is identified as a cause; otherwise, go to the next-to-the-last question.)

Where does interference between workers or work crews occur in the shipbuilding process?

____

____

When does this happen?

____

____

How do you handle it if it is a problem?

____

____

____

Which types of crews or trades are most compatible?

____

____

Which types of crews or trades are least compatible?

____

____

Is this considered a serious problem?

____

____

____

What type of organizational structure does your shipyard have?

( ) Heirarchical

( ) Project manager

( ) Area coordinator

( ) Matrix

( ) Other ______________________________

____

Who in the shipyard should we talk to if more details are needed? (Get name and phone number.)

____

____

____

____

____

Who should we contact for authorization to visit the yard?

____

____

____

____

____

CONCLUSION: (Thank the respondent for his participation)

APPENDIX D

SHIPYARDS INTERVIEWED

Shipyard	Size	Merchant	Naval
Bay Shipbuilding	Major	X	
Sun Shipbuilding	Major	X	
Bethlehem Steel	Major	X	
Ingall's Shipbuilding	Major		X
Todd Shipbuilding	Major	X	X
Jeff Boat	Int'm	X	
National Steel	Major	X	X
American Shipbuilding	Major	X	
Lockheed Shipbuilding	Major		X
Dravo Corporation	Int'm	X	
Bath Iron Works	Major	X	X
Equitable Shipyards	Int'm	X	
Levingston Shipbuilding	Int'm	X	
Alabama Shipbuilding	Int'm	X	
Zigler Shipyards	Small	X	
Avondale	Major	X	X
McDermott Shipyard	Small	X	
Nashville Bridge Company	Small	X	
Peterson Builders	Small	X	
Norfolk Shipbuilding	Int'm	X	
Newport News Shipbuilding	Major	X	X

APPENDIX C

A FRAMEWORK FOR ANALYZING HOW VARIATIONS
IN SHIPYARD WORKLOADS IMPACT
SHIPBUILDING COST

by

William Robert Terry

Department of Industrial Engineering and Operations Research
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

PREFACE

The Industrial Engineering and Operations Research Department's activities were divided into three phases. The first phase, which is reported in "A Diagnosis of the Workload Variation Problem in Shipbuilding", was designed to identify specific problems for further analysis. This analysis revealed the need for the following:

(1) a system for analyzing how variations in shipyard workloads affect shipbuilding cost;

(2) a shipyard planning system which could be utilized by shipyards to minimize the cost of adjusting to workload variations.

Phase 2, which is the subject of this report, focused on developing the framework of a system for developing transfer function models which can be used to develop the difference equations which describe how variations in shipyard workloads affect shipbuilding cost. Phase 3, which is described in "A Shipyard Planning System", focused on developing the framework of a shipyard planning system which shipyards could use to minimize the cost of adjusting to workload variations.

I. INTRODUCTION

The purpose of this paper is to develop a framework for analyzing how variation in shipyard workloads impact shipbuilding cost. Such analysis could be used by those responsible for establishing Navy shipbuilding budgets to analyze how alternative funding programs influence both procurement cost and mobilization potential.

In order to analyze how variations in workload affect shipbuilding cost, it was necessary to develop a means for quantifying the terms: (1) workload, and (2) shipbuilding cost. It was also necessary to establish a model building process for developing the difference equations which describe how workload variations dynamically affect shipbuilding cost.

II. OPERATIONAL DEFINITIONS

The first step towards quantifying workload, and (2) shipbuilding cost was to develop operational definitions for these terms. The process for developing an operational definition of a term was to first develop a precise phenomenological definition of the term. This definition will be used to construct an idealized measurement procedure where the only constraint would be whether it was physically feasible--for example, the information systems cost will not be considered at this stage. This idealized measurement procedure will then be used as a criterion for evaluating the relative merits of alternative measures which can be derived from currently available sources of data.

The term "workload" is defined by Urdang and Flexner (1969) as "the amount of work that a machine, employee, or group of employees can be or is expected to perform." In practice the amount of work which a man and/or machine system is expected to perform under a given set of conditions is specified by a production (or construction) schedule. This suggests that workload be redefined as the amount of work which a man and/or machine system is scheduled to perform during a specified time period under specified conditions.

In theory methods engineering can be used to determine the capacity of a production facility operating in a construction type environment similar to those encountered in shipbuilding (Parker and Oglesbuy, 1972). The major problem is that methods engineering has not been used to determine shipyard production capacities in the past (Bath Iron Works Corporation, 1977). Therefore, such information could not be obtained from historical data even if cost were of no concern. Another problem is that space and facilities are limited in most shipyards. This

creates problems in which workers in the same craft and in different crafts can interfere with the productivity of one another. Presently available methods engineering techniques are not capable of predicting *a priori* when and the extent to which such interference will result. However, time-lapse motion pictures have been used to obtain such information on an empirical basis for specific situations in civil construction (Parker and Oglesby, 1972).

In most organizations scheduling is performed by a staff group such as production control, production planning, or production scheduling, who produce formal documents known as production schedules. Once the schedule work has been accomplished, the production schedule is of little or no value. When the value of the information contained in a document is less than the cost of storing it the document should be destroyed. Therefore, the amount of historical data on manufacturing facility workloads will be limited.

The term "shipbuilding cost" was decomposed into its constituent parts. Shipbuilding is an umbrella term which refers to the activities involved in constructing a naval vessel. However, the set of activities necessary for constructing one ship may differ greatly from that of another ship. Execution times for ship constructions are likely to decrease as the shipyard becomes more experienced due to the "learning" effect. This is especially pronounced with the construction of identical (or near identical) vessels. This often leads to method improvements in the construction of subsequent ships. Difficulties arise in predicting costs when the same work on two identical ships can be performed by different production facilities which utilize vastly

different work methods. Also, weather conditions can also necessitate utilizing different production facilities and work methods for accomplishing the same work package on a particular ship.

The term "cost" is defined by Urdang and Flexner (1969) as "the price paid to acquire, produce, accomplish, or maintain anything". Note that this definition gives the reader the choice between the following words: (1) acquire; (2) produce; (3) accomplish; or (4) maintain. In choosing the most appropriate word it will be helpful to consider the wide variety of activities which must be performed in building a ship. Raw materials and purchased parts components and systems are acquired from outside resources. The raw materials are first converted into manufactured parts. If a large number of identical or highly similar parts are produced successively on a periodic basis, then the conversion process will be referred to as a <u>continuous production process</u>. If only one or a limited number of copies of a part are made at one time the conversion process will be referred to as a <u>discrete production process</u>. A ship is built by assembling manufactured purchases (or government supplied) parts, components, and systems according to a specified plan. The process of assembling is referred to as the construction process. In order to perform these activities efficiently it is necessary for the shipyard to maintain its facilities.

The above definition of cost is too limited to account for the wide variety of activities which must be performed in building a ship. In order for the definition to encompass those activities the definition should be modified so that the reader is given a choice between the following words: (1) acquire; (2) convert; (3) construct; and (4)

maintain. Therefore, the above definition of cost should be modified so as to account for each of the above activities.

The price associated with accomplishing each of the above activities will typically be measured in monetary units. This poses a problem since the value of all monetary units have been erroded by inflation during recent years. Fortunately, various indices are available which can be used to adjust for inflation. Another problem arises due to the fact that payments made for accomplishing the above activities are typically spread out over a three to five year time period. Each payment represents the loss of the opportunity to utilize the funds in alternative ways.

The price paid to accomplish a given activity can be classified according to whether the outlay was made during the present period or in some previous period. For example, wages will be paid in the current period, while the cost of acquiring a capital asset may have been incurred during some previous period.

The cost of acquiring a capital asset equipment consists of the purchase cost, transportation cost and installation cost. From a legal standpoint the costs are incurred at the time title changes hands. The mere fact that a machine is purchased on credit with payments being spread out over time does not alter the fact that the cost of acquiring a capital asset is incurred at the time the title changes hands. However, such costs, typically incurred in the past, complicates the task of determining the cost associated with accomplishing the activities performed during the present period.

The problem revolves around determining the value of the capital assets which were consumed as a result of performing the current periods

activities. All solutions are arbitrary to a certain extent. The "generally accepted" accounting practice is to record the value of the asset at its original acquisition cost. The value of the asset is then spread over its useful life according to some depreciation method. Depreciation methods can be classified as either straight line or accelerated methods. The straight line method changes an equal amount of the assets original value to each year of its useful life. In relation to this straight line method the accelerated methods charge higher amounts during the early years and lower amounts during the latter years of the assets life.

The "generally accepted" accounting practice of recording the value of an asset at its original acquisition cost is undesirable from the standpoint that the total amount of the depreciation charges will not be sufficient to cover the cost of acquiring an identical machine at the time the asset has been depreciated to zero. Therefore, it appears that current accounting practices are underestimating the value of the capital assets which are consumed in the manufacturing process. An alternative method of calculating depreciation charges has been proposed but at present has not found wide acceptance. This method involves basing depreciation charges on the replacement value of the asset rather than on its original cost.

The analysis of the terms shipbuilding and cost provided a basis for synthesizing the following phenomenological definition of shipbuilding cost.

Shipbuilding cost is the amount paid for performing the following activity involved in building a ship:

(1) acquiring raw materials, and purchased parts, components, and systems from outside sources;

(2) converting raw materials into manufactured components;

(3) assembling and joining the various manufactured parts, and purchased and/or government supplied parts, components, and systems according to a specified plan;

(4) maintaining manufacturing facilities where the price is adjusted for the effects of inflation, and the time value of money, and where depreciation charges which are included in the price are based on the cost of replacing the capital assets.

In theory shipbuilding cost as defined above could be calculated from presently available data. However, in practice, it would be difficult to determine the replacement cost for assets during prior time periods. Thus, the amount of historical data on shipbuilding cost will be so limited.

One strategy for coping with the limited data problem is to identify historically available variables which logically would be expected to behave in a similar way as manufacturing facility workload and shipbuilding costs. Such variables will be referred to as "proxy variables". A proxy variable for manufacturing facility workload is suggested by the fact that this quantity was defined in terms of the amount of work that a man and/or machine system is scheduled to perform during a specified time period. In a labor intensive industry such as shipbuilding it is reasonable to assume that the amount of work that management expects to be accomplished will be roughly proportional to the number of workers

assigned to the manufacturing facility. Monthly data on the number of production workers in the shipbuilding industry can be obtained from the Bureau of Labor Statistics. This data series was started in 1947. Similar data is also available at the shipyard level. However, special permission will be needed to gain access to this data.

A proxy variable for shipbuilding cost is suggested by the fact that approximately 77 percent of the value added by the shipbuilding industry is due to labor (Martin, 1977). Furthermore, this quantity has remained remarkably stable since 1954. Since labor cost dominates value added, this suggests that constant dollar labor cost per ton might be used as a proxy variable for shipbuilding cost. Shipbuilding labor cost in current dollars are reported on monthly basis by the Bureau of Labor Statistics. This data can be converted to constant dollar labor cost by a price index (such as the Consumer Price Index) as a deflator. The labor cost is available on a monthly basis. The labor cost data series was started in 1948. However, tonnage data for shipbuilding are not available on a monthly basis.

The failure to find adequate proxy variables for workload and shipbuilding cost which could be derived from historical data signaled the need for a fresh approach. This led to a qualitative analysis of the ways in which workload variations could influence shipbuilding cost. The results of this analysis are described in the following section.

III. A QUALITATIVE ANALYSIS OF THE IMPACT OF WORKLOAD VARIATIONS ON SHIPBUILDING COST

In the preceeding section operational definitions for workload and shipbuilding cost were developed. The definitions were then used as criteria for evaluating the relative merits of alternative proxy measures which could be derived from historical data. The failure to find adequate proxy variables which could be derived from historical data indicated the need for a fresh approach. This section describes the approach which was adopted. This approach was to analyze in a qualitative fashion the ways in which workload variations could influence shipbuilding cost.

In the previous section workload was defined as "the amount of work which a man and/or machine system is scheduled to perform during a specified time period under specified conditions". This suggests that workload variation is a change in the scheduled amount of work. The fact that production/construction schedules are established by shipyard management prompted a search for the factors which could cause production/construction schedules to be altered. This analysis revealed that changes in the demand for ships is the prime factor which causes schedule alterations. Shortages of labor and materials were also found to be important factors.

The above analysis indicated that the demand for ships should be regarded as a causal variable and that workload should be treated as an intervening variable. The next step was to analyze how changes in the demand for ships impacts shipbuilding cost. This analysis that a change in demand could cause reaction by shipyard management and shipyard workers which could affect shipbuilding cost. It was found that

shipyard managers could respond to a change in demand by utilizing one or more of the following:

(1) layoff surplus workers;

(2) hire new workers;

(3) rehire workers previously laid off;

(4) work overtime;

(5) work less than 40 hours per week;

(6) subcontract work;

(7) use surplus production workers to do maintenance work on shipyard facilities.

Certain costs will be associated with utilizing each of the strategies. Increasing the size of the work force can involve the following activities: (1) recruiting; (2) interviewing; (3) testing; (4) performing medical exams; (5) placing; and (6) training. The following often result when the size of the workforce is decreased: (1) exit interviews; (2) separation payments; (3) increased unemployment insurance premiums; and (4) a bad image in the local labor market. Hancock (1971, p. 7-113) stated that the cost for "the leaving of one person and the hiring of a new one are from $600 to $2,000". These costs do not account for the hyper inflation which has transpired since 1971. If an adjustment for this is made then the current dollar equivalent of these costs would be approximately $1,050 to $3,500. Working overtime will require the payment of overtime premiums. Furthermore, efficiency is likely to drop. Working less than 40 hours per week will tend to increase turnover cost. Subcontracting work can involve additional cost since the subcontractor must earn a profit. In addition the subcontractor is likely to be less

efficient than the shipyard. Utilizing skilled construction workers to do maintenance work on shipyard facilities will increase cost if such work could be done equally well by less skilled workers. Obviously, a shipyard would like to identify the combination of the above options which will minimize total relevant cost. A system for doing this is described in Terry (1979).

It was also found that a change in demand could motivate present shipyard workers to act so as to protect their interest. For example, if workers suspect that they are working themselves out of a job they will tend to slow down to protect their jobs. In addition, some of the workers will probably quit to accept more secure jobs. This could create disruptions which increase cost. In addition memories of previous layoffs will make it more difficult for a shipyard to recruit new workers once demand increases. Furthermore, the output rate of the shipyard will not immediately increase once new employees are hired. Instead, it will tend to gradually increase as the new employees learn their jobs and are integrated into the workforce.

The above analysis suggested the systems model depicted in Figure 1 on the following page. This model contains three black boxes which represent shipyard management, present shipyard workers and potential shipyard workers. The demand for ships serves as an input to these black boxes. Each of these black boxes transforms the input into a variety of outputs. The output for shipyard management can be any combination of the following: (1) layoff unneeded workers; (2) hire new workers; (3) rehire workers previously laidoff; (4) work overtime; (5) work short week; (6) subcontract; and (7) use surplus workers to do maintenance work on shipyard facilities. The output for present shipyard workers consists of

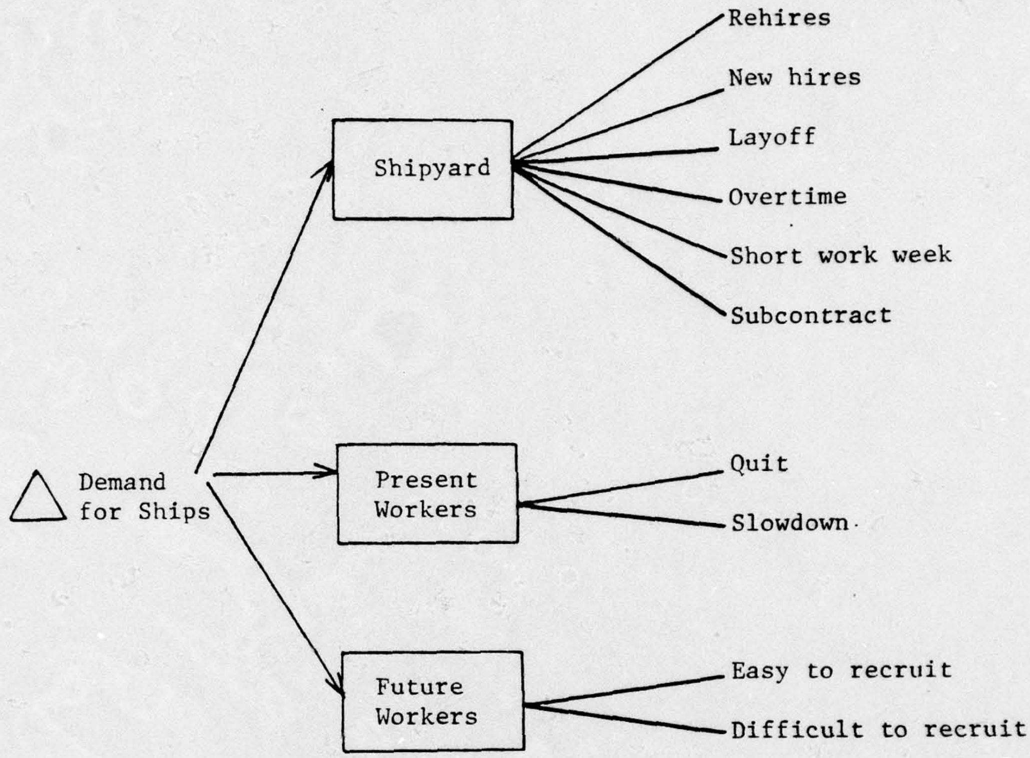


Figure 1. Systems model of the way changes in the demand for ships impacts shipbuilding cost.

decision to: (1) slow down to stretch out work; and (2) quit to accept more stable employment. The output for future shipyard workers consists of the formation of opinions regarding the relative desirability of working for a shipyard. These opinions, if negative, could make it more difficult to recruit additional workers.

The above analysis suggested that order backlog could be used as a proxy variable for the demand for shipyard services. Order backlog data for the shipbuilding and repair industry is maintained on a monthly basis by the Census Bureau in their Current Industrial Reports (Census Bureau).

The above analysis also prompted a search for data from which quantitative measures of the outputs of the black boxes in Figure 1 could be obtained. This search revealed that the following variables are recorded on a monthly basis by the Bureau of Labor Statistics in their Employment and Earnings Series (Bureau of Labor Statistics):

(1) production-worker average weekly hours;

(2) production-worker average weekly overtime hours;

(3) accession (permanent and temporary additions including both new and rehired employees) per 100 employees;

(4) new hires (permanent and temporary additions of new employees) per 100 employees;

(5) separations (terminations of employment initiated by either employer or employee) per 100 employees;

(6) quits (terminations of employment initiated by employees) per 100 employees;

(7) layoffs (suspensions without pay lasting or expected to last more than 7 consecutive calendar days, initiated by the employer

without prejudice to the worker) per 100 employees.

It also provides a basis for calculating rehires:

rehires = accession - new hires.

Furthermore, the extent to which short work weeks are being utilized can be measured in terms of the amount by which the production-workers average weekly hours falls short of 40. However, no means was found for quantifying: (1) the extent to which present shipyard workers slow down in order to protect their job; (2) the extent to which potential shipyard workers are easy or difficult to recruit; and (3) the extent to which shipyards use more or less subcontracting than normal.

IV. MODEL BUILDING PROCESS

The purpose of this section is to describe a process which can be used to develop models for analyzing how both shipyard management and actual and potential shipyard workers react to changes in shipyard order backlogs. Management can react by laying off unneeded workers, hiring new workers or recalling old workers, working overtime, or reducing the length of the workweek. Actual shipyard workers can react by quitting or slowing down in order to stretch their work out. Potential shipyard workers can either respond or not respond to shipyard recruitment efforts. This suggests the need for models to predict the behavior of (1) shipyard workers and (2) shipyard management.

The strategy will be to develop separate models to explain how each of the following proxy variables for shipbuilding cost:

(1) production worker-average weekly hours;

(2) accessions;

(3) new hires;

(4) separations;

(5) quits;

(6) layoffs;

are influence by order backlog. In developing these models each of the above proxy variables for shipbuilding cost will be regarded as an output of a black box. Each of these black boxes will have the same input: order backlog. These black boxes represent the process whereby changes in the input variable (order backlog) are transformed into changes in the output variable (one of the proxy variables for the component of shipbuilding cost which can be influenced by variations in the demand for shipyard services.

The task of developing a mathematical model which adequately describes the transformation is complicated by the following factors:

(1) A change in the input will not necessarily impact the output immediately. Instead, the reaction can be delayed. This delayed reaction effect is illustrated by Figure 2.

(2) The impact of a one time change in input on the output does not have to be concentrated at a single point in time. It is quite possible for a change in the input at a single point in time to be spread over several time periods. This partial adjustment process is illustrated by Figure 3.

(3) The point at which a change in input creates the maximum impact on the output is not known. This uncertainty regarding the location of the point of maximum impact is illustrated by Figure 4.

(4) The buildup to the point of maximum impact can be either slow and gradual or fast and abrupt or some combination of these two extremes. The varability in the rate of buildup to the point of maximum impact is illustrated by Figure 5.

(5) The decline from the point of maximum impact can likewise be either slow and gradual or fast and abrupt or some combination of these two extremes. The variability in the rate of decay from the point of maximum impact is illustrated by Figure 6.

In order to cope with this situation it will be necessary to have a model building process which can respond to any mixture of the above types of behavior. Such a model building has been developed by Box and Jenkins (1970) and is referred to as the transfer function model building process. Since this process utilizes the Box-Jenkins univariate model

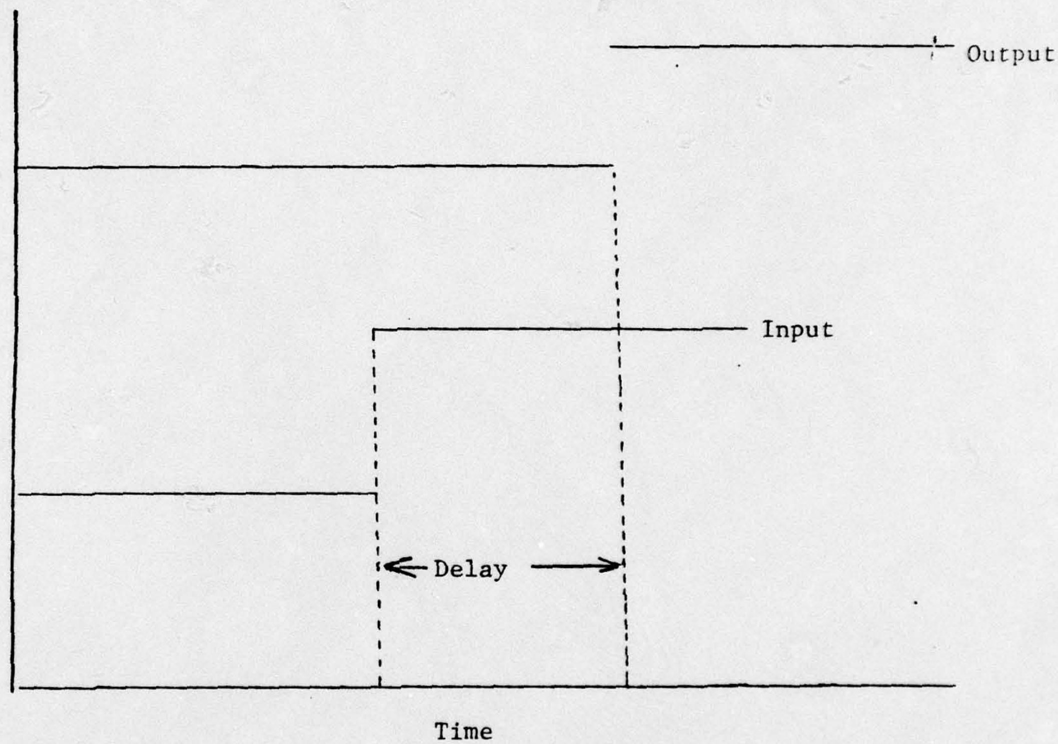


Figure 2. Delayed reaction of a change in output to a change in input

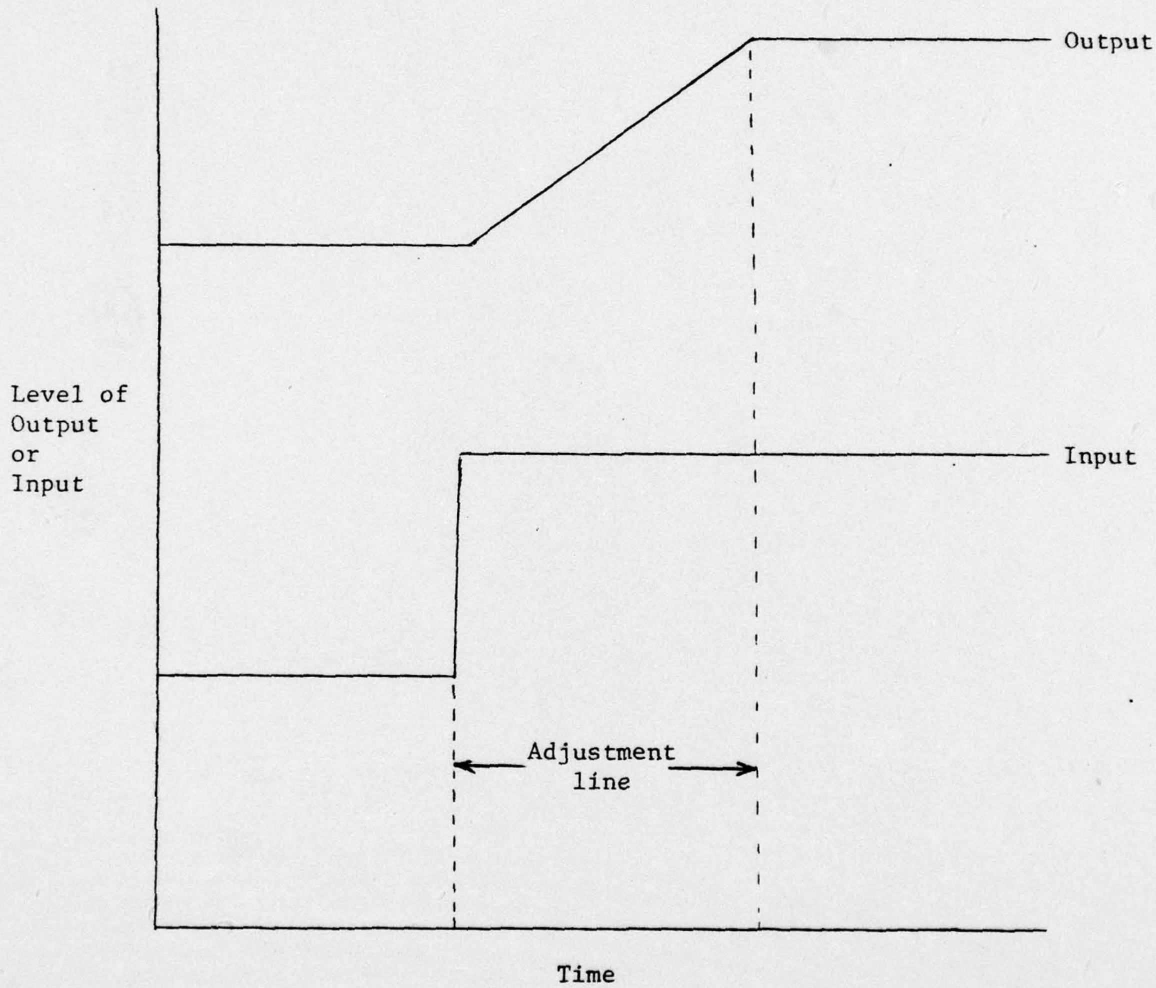


Figure 3. Reaction of output to a change in input is spread over several time periods

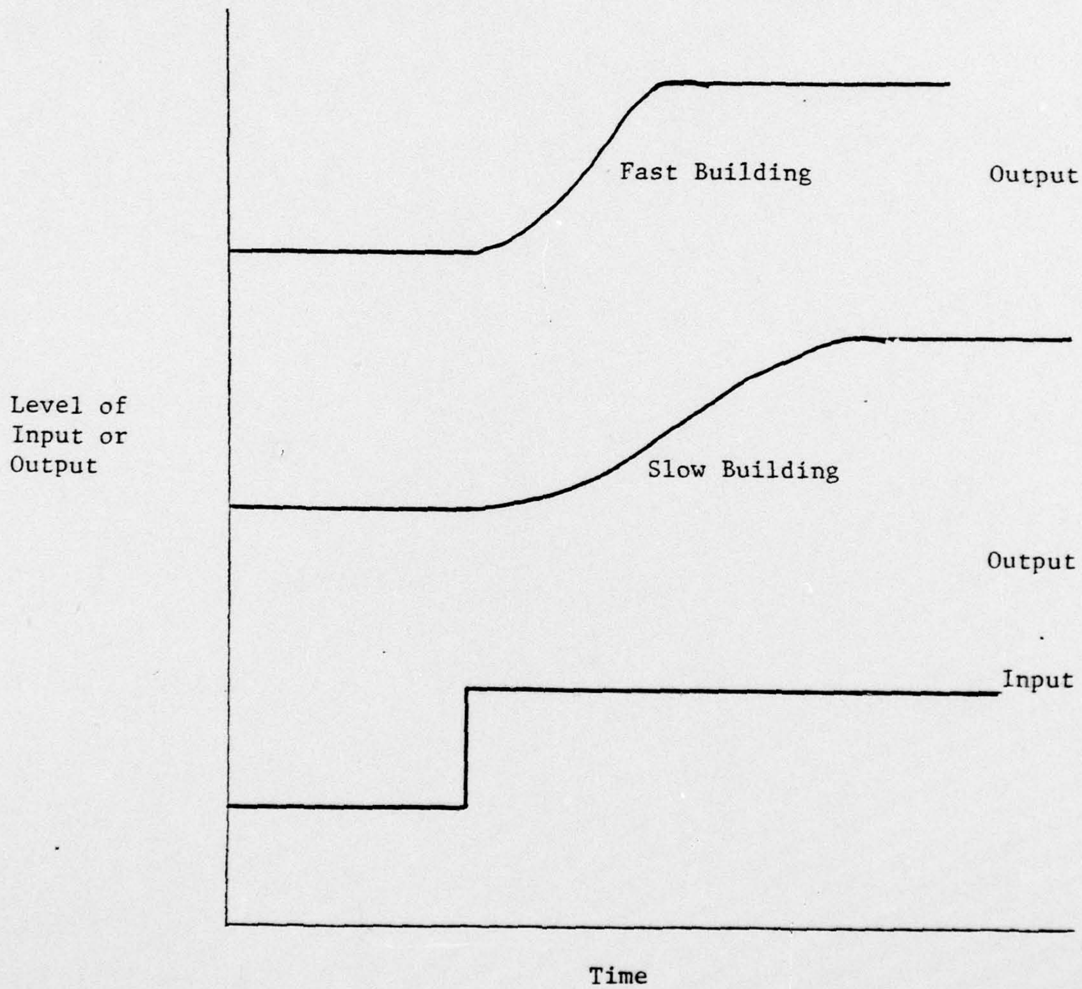


Figure 4. Comparison of two different rates of buildup to the point of maximum impact

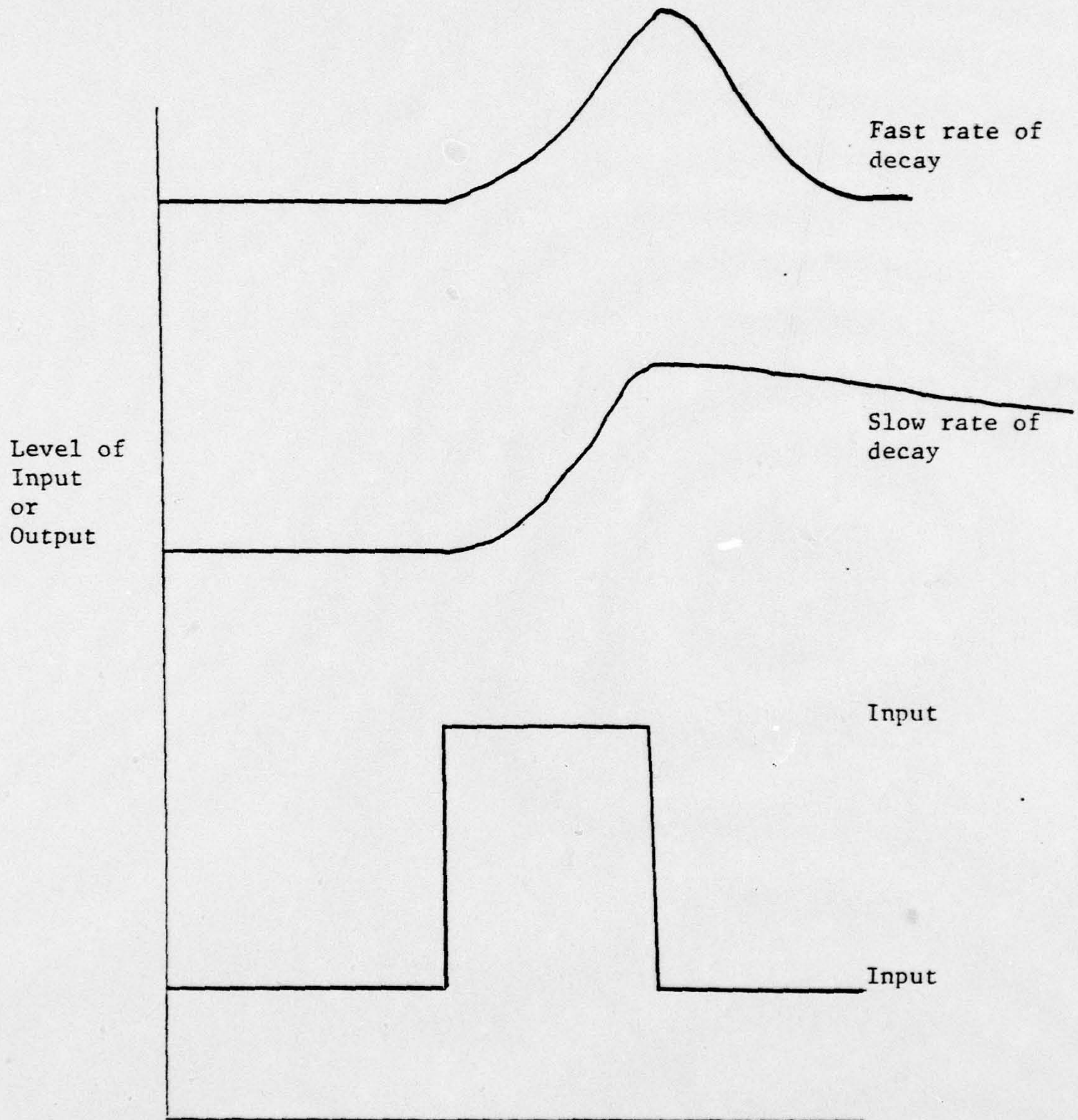


Figure 5. Comparison of two different rates of decay from the point of maximum impact

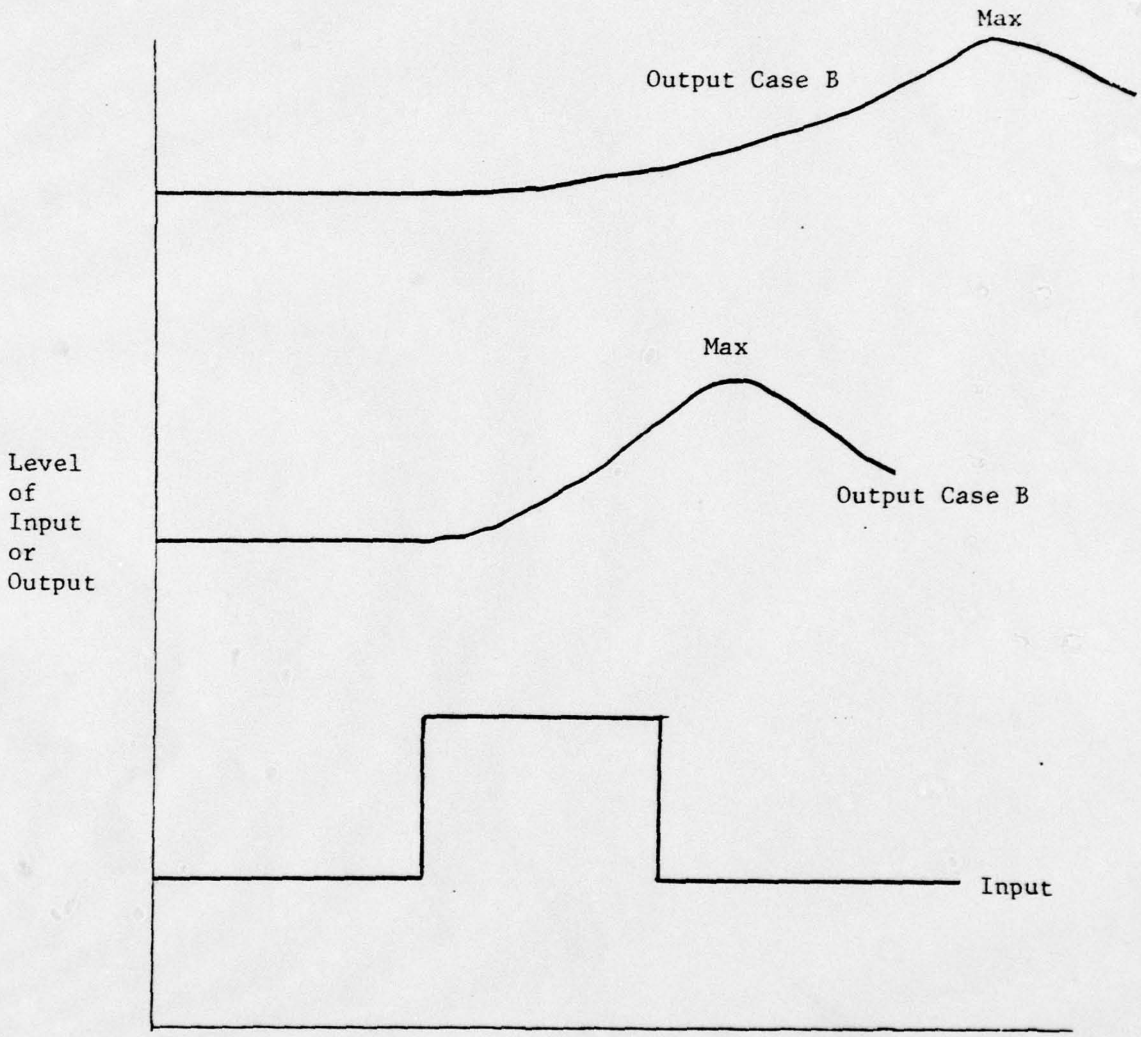


Figure 6. Point of maximum impact can vary.

building process this process will be described first.

An Overview of the Box-Jenkins Univariate Method

A single exogenous shock can affect the behavior of a system in a variety of ways. If a shock alters the structure of the system, then its effect on the systems behavior will be long term or permanent. A shock which does not alter the structure of the system will produce only short term changes in the behavior. These short term effects on system behavior can either end abruptly after a specified period of time or gradually decay. Figures 7, 8, and 9 respectively illustrate the permanent change, gradual decay, and abrupt termination reaction patterns.

In order to predict the future behavior of a system it is not necessary to determine what causes, or from where, an exogenous shock came. It is more important to determine how the system reacted to an exogenous shock regardless of its cause or source. However, if the cause of a shock is known and if the occurrence of the shock is preceded by an early warning signal then it might be possible to predict when the shocks would occur. If this is the case then this knowledge can be used to predict the future behavior of the system of interest. If a particular type of shock always causes the system to react in a particular way, then the response of the system to that type of shock can be described by a deterministic model.

If for every type of shock the reaction of the system can be described in terms of a deterministic model, then all aspects of the behavior of the system can be described completely by the collection of all such models. However, such a collection of deterministic models

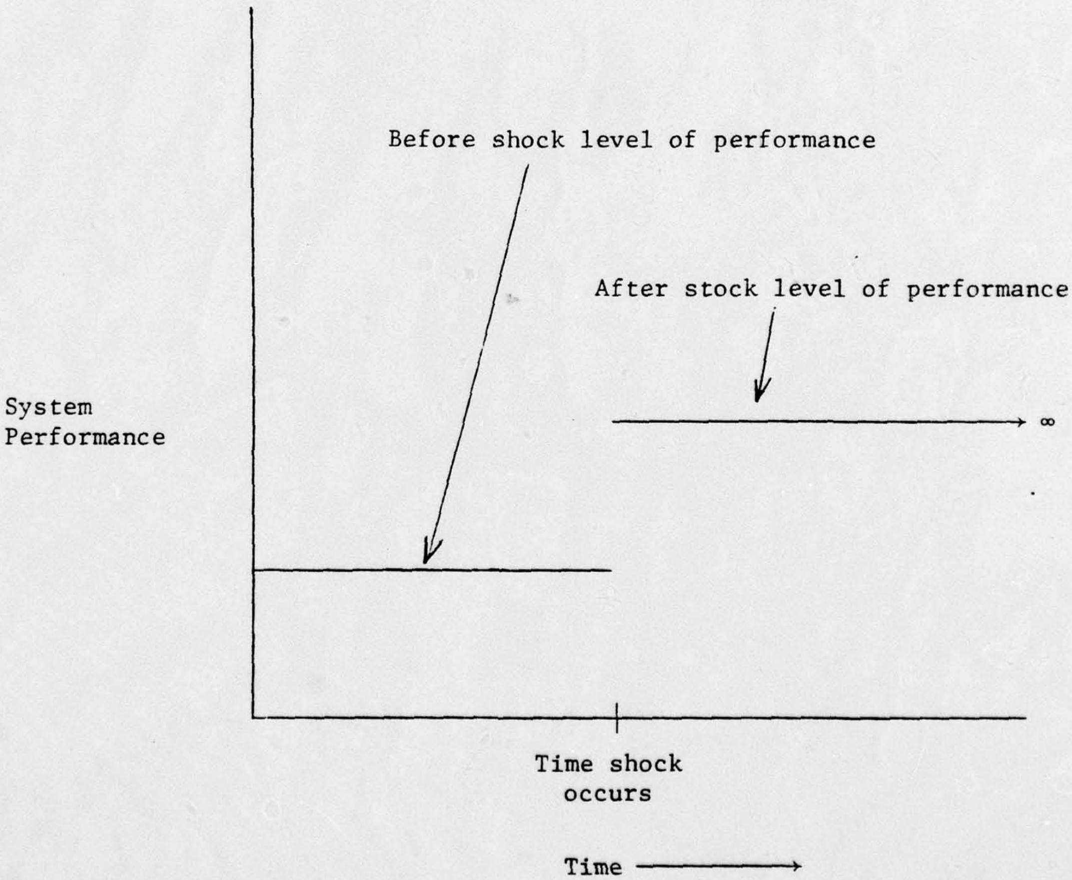


Figure 7. Exogoneous shock alters structure of system which cause permanent change in system behavior

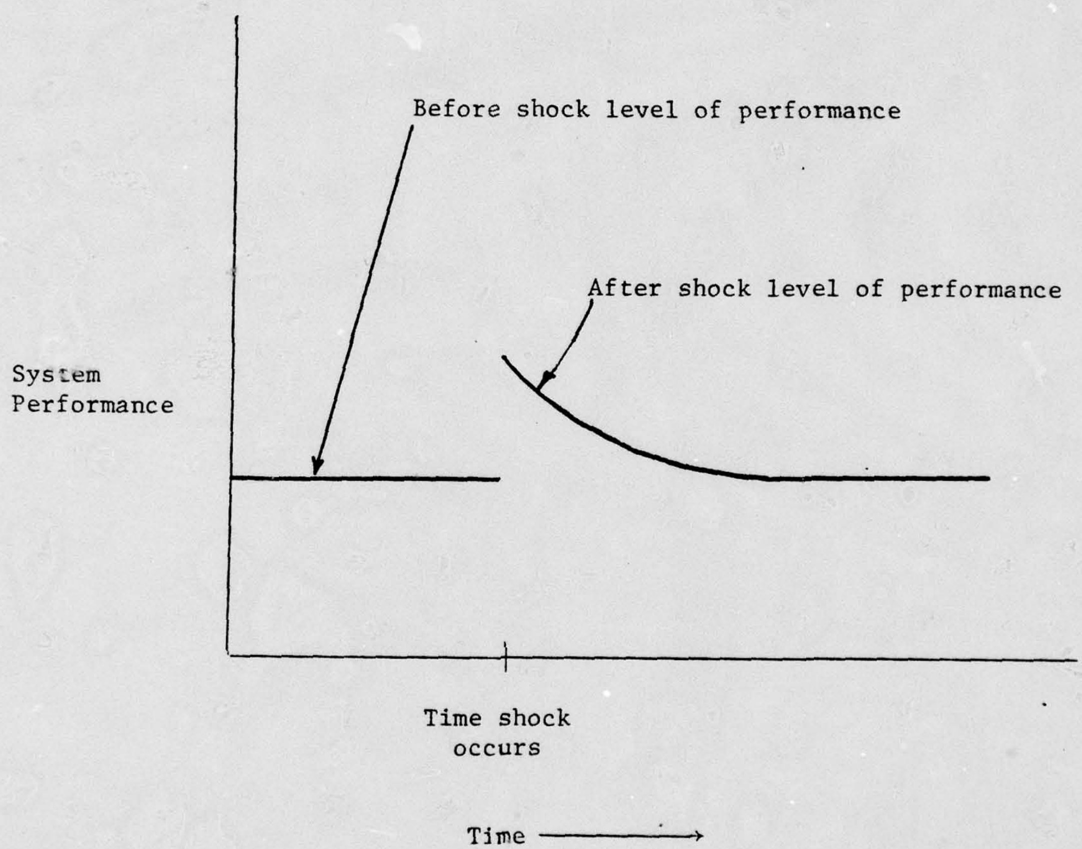


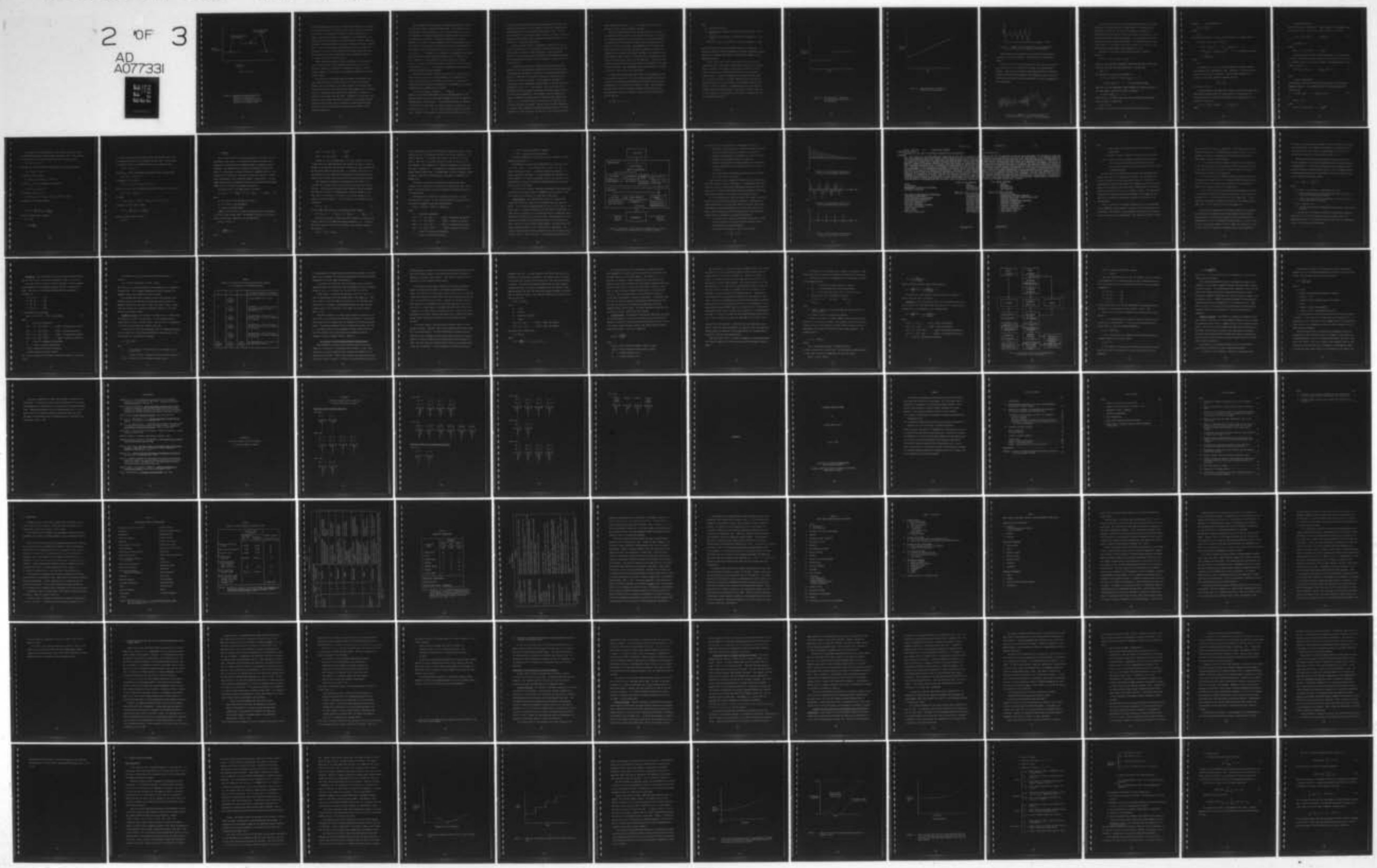
Figure 8. Exogoneous shock affects system behavior in a manner which gradually decays with the passage of time

AD-A077 331 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 13/10
ANALYSIS OF THE COST OF VARIABLE WORKLOADS ON SHIPBUILDING.(U)
NOV 79 A H MAGNUSON , R W TERRY N00014-78-C-0411

UNCLASSIFIED VPI-AERO-103 NL

2 OF 3

AD
A077331



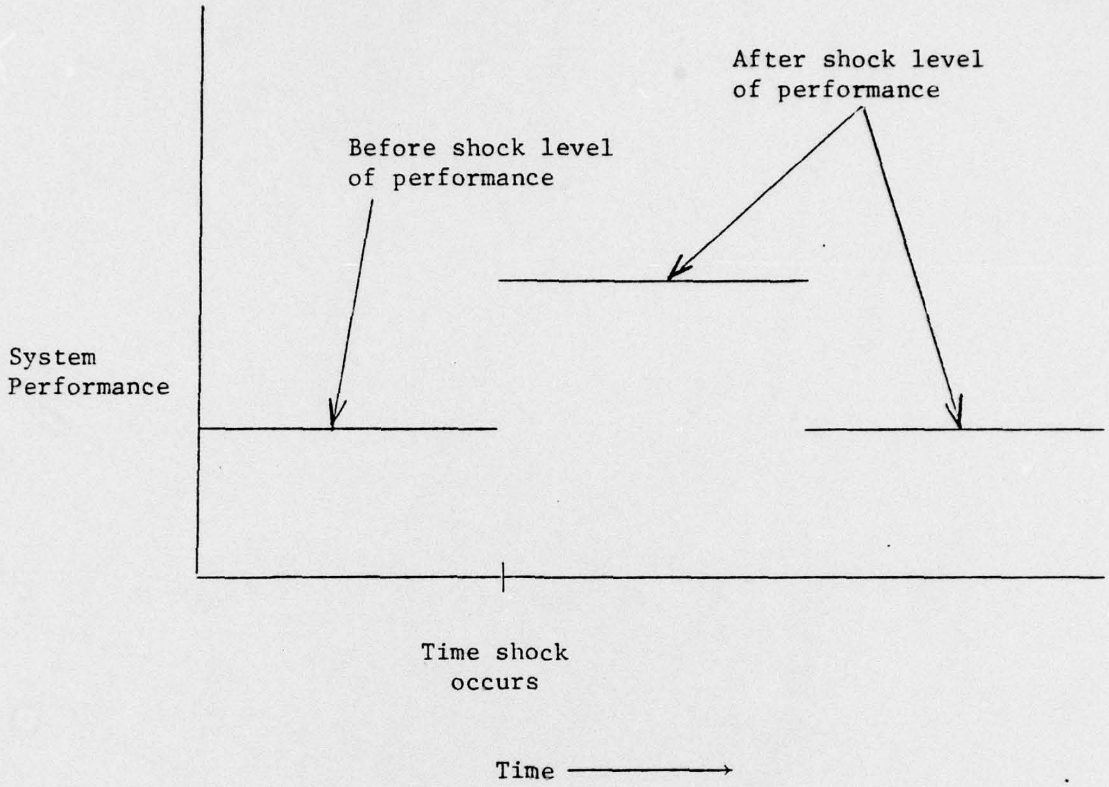


Figure 9. Exogoneous shock affects system behavior in a manner which persists at a constant level for a period of time and then abruptly returns to the original level

will not necessarily enable one to predict future behavior of the system with complete certainty. When some or all of the shocks are not measurable it will not be possible to predict the future behavior of the system. Even when all shocks can be measured, this information is not useful for predictive purposes if the time required to make a prediction exceeds the time required for the shock to influence the system. Furthermore, if the cost of measuring the shocks plus the cost of using this information to predict future behavior of the system exceeds the value derived from more accurate predictions, then a deterministic model of the systems behavior will not be useful.

Useful prediction models can often be developed for situations in which either or both of the following conditions occur: (a) it is either too expensive or impossible to measure the shocks; or (b) the system's reaction to a shock can not be described adequately by a deterministic model.

The strategy for developing predictive models in the above situations exploits the fact that the effects of a shock on the system's behavior tend to be spread out over some interval of time rather than being concentrated at a particular point. This suggests that the current value of a time series which describes the behavior of a system is a function of the current and past shocks. Therefore, it follows that the sequence of values which describes the behavior of the system contains information which can be used to establish a stochastic process model which tells how the time series which describes the behavior of the system was generated.

Box and Jenkins (1970) developed a systematic procedure for establishing such a model for any given time series. In its simplest form the Box-Jenkins method considers the case in which there is no quantitative information available regarding the exogenous forces which affect the behavior of the system. In any given time period it is quite possible for a number of these exogenous forces to simultaneously act on the system. The net effect of all the forces acting on the system during any given time period will be denoted by a_t. The time series a_t, a_{t-1}, a_{t-2}, . . . is assumed to be a sequence of independent, identically distributed Normal random variables with mean zero and variance σ_a^2. Such a sequence of random variables is often referred to as "white noise." The time series which describes the behavior of the system will be denoted by z_1, z_2, . . . z_t and will be regarded as a realization of a jointly distributed random variable.

The Box-Jenkins method is based on the idea that a time series in which successive values are highly dependent can be regarded as the result of passing white noise through a linear filter. This linear filtering operation considers the behavior of the system to be a linear combination of the present and past shocks,

$$z_t = \mu + a_t + \psi_1 a_{t-1} + \psi_2 a_{t-2} + \ldots + \psi_N a_{t-N} \tag{1}$$

where μ is the level of the process, ψ_i's are weights applied to the previous shocks, the sum of which must converge, and N is the number of observations in the time series. If this model were used to represent the behavior of a time series, it would be necessary to estimate N + 2 parameters (μ, Ψ_1, Ψ_2, ... Ψ_N, σ^2). This exceeds the number of observations. However it is possible to simplify the above model when it can

be assumed that the mean and variance/covariance matrix (of the joint probability distribution of the stochastic process which generated the time series) exist and are invariant with respect to time. A time series generated by a stochastic process for which the mean and variance/covariance matrix exists and is invariant with respect to time is referred to as a stationary time series.

In order to explain why it is necessary to require that the time series be stationary, it will be helpful to first briefly describe the process used to establish a simplified model. Each of the steps involved in this process as well as methods for identifying and coping with nonstationary time series will be discussed in greater detail in later sections.

The Box-Jenkins process for simplifying the model in Equation 1 makes use of the autocorrelation function (acf) and the partial autocorrelation function (pacf) as the means for tentatively identifying which of a large family of stochastic models best accounts for the behavior of a given time series. The acf measures the degree of association or mutual dependence between values of the same time series separated by lags 1, 2, --- time periods. The ℓth term in the acf represents the product moment correlation coefficient between values of the time series separated by ℓ time periods. The pacf measures the degree of association between values of the time series separated by lags 1, 2, --- time periods where the effects of all lags less than the lag of interest are removed. The ℓth term in the pacf represents the product moment correlation coefficient between values of the time separated by ℓ time period with the effects of the correlation between

values separated by lags 1, 2, ---, ℓ-1 removed. The acf and pacf describe how well a system remembers its past.

The model simplification process for doing this first involves calculating the acf and pacf for the observed time series. The shapes of the sample estimates of the acf and the pacf are then compared with the shapes of the theoretical acf's and the pacf's derived from the family of stochastic processes. The parameters of the linear filter whose theoretical acf and pacf best match the sample acf and pacf are estimated by a nonlinear least squares technique. The adequacy of the fitted model is then checked by a procedure which necessitates calculating the autocorrelation function of the residuals. If the fit is not adequate the autocorrelation function is used to determine how the model should be modified. Once an adequate model has been found, it is used to forecast future values of the time series.

In order for the above approach to work, it is necessary for the first and second moments of the joint probability density function of a sequence of observations generated by the stochastic process under consideration to be invariant with respect to time. The requirement that the second moment be invariant results from the fact that the autocorrelation function is defined in terms of the autocovariances and the variance:

$$\rho_i = \frac{\gamma_i}{\gamma_0} \quad \text{for } i = 1, 2, \ldots$$

where

γ_0 = variance of process

γ_i = autocovariance between two observations separated by i time periods

ρ_i = autocorrelation between two observations separated by i time units.

Since both γ_0 and γ_i are defined in terms of the mean it follows that the first moment of the time series must also be invariant. A process for which the first two moments of its joint probability density function are invariant with respect to time will be referred to as a stationary process.

Nonstationarity will always result when the mean of a process changes over time. This can occur when either the level of the process abruptly changes or the level of the process is subject to a trend. Figure 10 illustrates a situation where the level of the process suddenly shifts. Figure 11 illustrates a situation where the level of the process is subject to a trend. When this occurs the variance and autocovariances of the process are not meaningful since they are defined in terms of the mean. A nonstable mean is not the only way nonstationarity can manifest itself. Even when the mean is stable it is still possible for the variance of the process to change over time as illustrated by Figure 12.

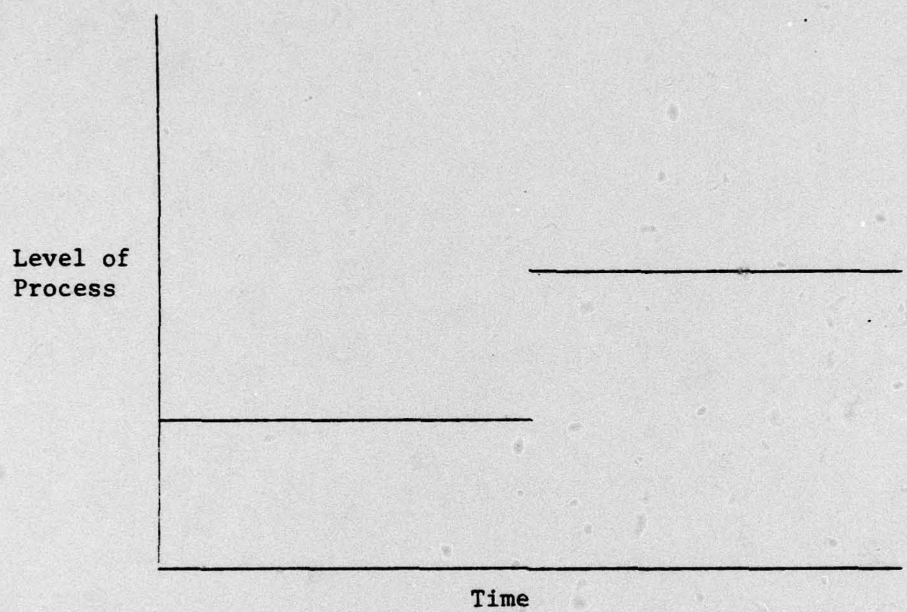


Figure 10. Nonstationaity is caused by the sudden shift in the level of the process

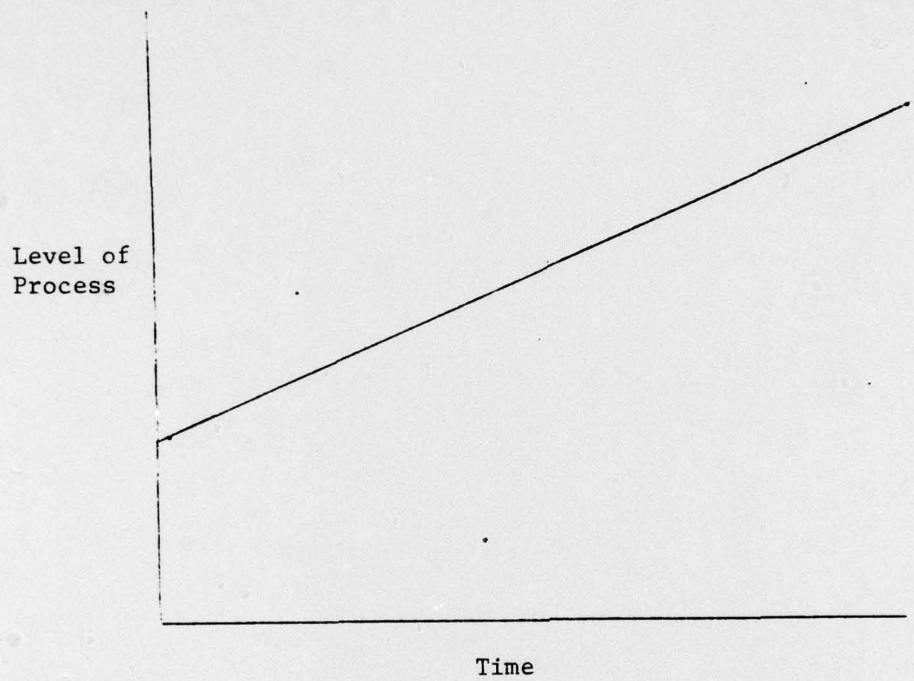


Figure 11. Nonstationarity is caused by a trend in the process level.

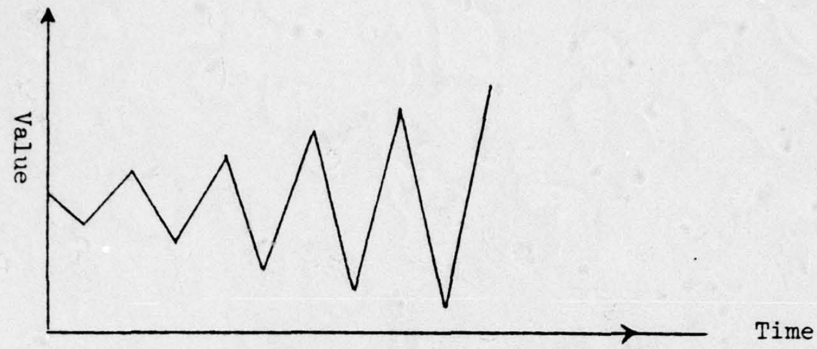


Figure 12. Example of a Time Series which is Nonstationary due to the Fact that the Variance is Heterogeneous

Nonstationarity also manifests itself when the autocovariance structure of the process changes. This situation is illustrated by Figure 13.

If the stochastic process generating the time series is nonstationary, then it will not be possible to calculate the autocorrelation function. When this is the case the Box-Jenkins method for developing a model for describing the process is not applicable since it uses the acf and pacf to identify a tentative model and to check the adequacy of the fitted model.

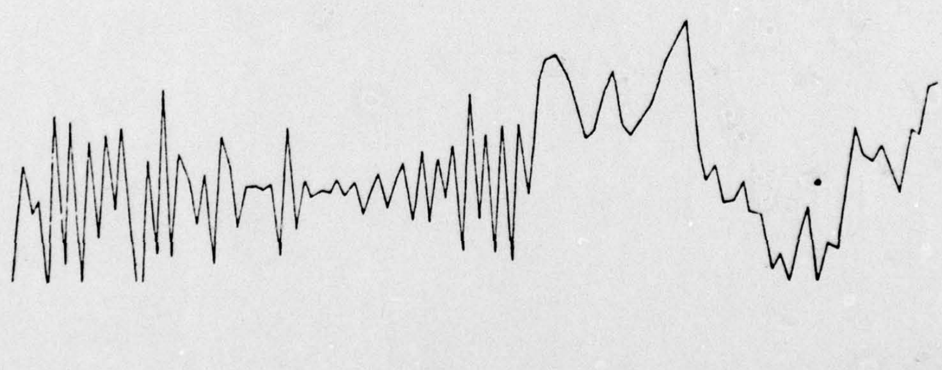


Figure 13. Example of a Time Series which is Nonstationary due to a Change in the Autocovariance

All models considered by the Box-Jenkins method must be stationary. The task of verifying that each of these models is stationary can be simplified by exploiting the fact that all models considered by the Box-Jenkins method are special cases of the linear filter process. Thus, if the linear filter process can be shown to be stationary, then all of its special cases will also be stationary. To establish that the linear filter process is stationary it will be necessary to show that its mean and variance/covariance matrix are independent of time.

The mean of the linear filter process described in Equation 1 given by:

$$E(z_t) = \mu + E(a_t + \psi_1 a_{t-1} + \psi_2 a_{t-2} + \ldots)$$

Since the a_t's represent independent random drawings from a Normal distribution with mean zero and variance σ_a^2 it follows that

$$E(z_t) = \mu \tag{2}$$

The variance of the process is defined as:

$$\gamma_0 = E\,\{z_t - E(z_t)\}^2 = E\,\{a_t + \psi_1 a_{t-1} + \ldots\}^2$$

$$= E\,\{a_t^2 + \psi_1^2\, a_{t-1}{}^2 + \ldots\} + E\,(\text{cross product terms})$$

Since the a_t's are independent random variables the expected values of the cross product terms will be zero. Therefore,

$$\gamma_0 = E\{a_t^2 + \psi_1^2 a_{t-1}{}^2 + \ldots\}$$

Since the a_t's are random selections from a probability distribution with zero mean it follows that

$$E(a_t{}^2) = \sigma_a{}^2$$

Therefore, the variance of the linear filter process described in

Equation 1 can be expressed as

$$\gamma_0 = \sigma_a^2 \sum_{i=0}^{\infty} \psi_i^2 \tag{3}$$

where

$$\psi_0 = 1$$

The covariance between z_t and z_{t-j} can be derived in a similar fashion

$$\gamma_j = E\{z_t - E(z_t)\}\{z_{t-j} - E(z_{t-j})\}$$

$$= E\{(a_t + \psi_1 a_{t-1} + \ldots)(a_{t-j} + \psi_1 a_{t-j-1} + \ldots)\}$$

$$= E\{(\psi_j a_{t-j}^2) + (\psi_1 \psi_{j+1} a_{t-j-1}^2) + \ldots\} + E \text{ (cross product terms)}$$

$$= \sigma_a^2 \sum_{i=0}^{\infty} \psi_i \psi_{i+j} \tag{4}$$

where

$$\Psi_0 = 1$$

From Equations 2, 3, and 4 it can be seen that the mean, variance, and covariances are independent of time. Therefore, it follows that the linear filter process is stationary. The following discussion will utilize the back shift operator B defined such that

$$B^k z_t = z_{t-k}$$

to simplify notation.

A special case of the linear filter model is the moving average (MA) model which postulates that the current value of a time series is a linear function of its previous disturbances. The general form of an MA model of order q is:

$$z_t = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \ldots - \theta_q a_{t-q} + \mu \tag{5}$$

where

μ = mean of MA process.

MA(q) will be used to denote a q^{th} order MA model. The backshift operator B can be used to obtain a more compact expression for MA(q)

$$z_t = (1 - \theta_1 B - \theta_2 B^2 - . . . . - \theta_q B^q)a_t + \mu \qquad (6)$$

or

$$z_t = \theta(B)a_t + \mu$$

where

$$\theta(B) = (1 - \theta_1 B - \theta_2 B^2 - . . . . - \theta_q B^q)$$

Another special case of the linear filter model is the autoregressive model (AR) which postulates that the current value of a time series is a linear function of all its past values. The general form of an AR model of order p is:

$$z_t = \phi_1 z_{t-1} + \phi_2 z_{t-2} + . . . + \phi_p z_{t-p} + a_t + \delta \qquad (7)$$

where

δ = mean of AR process.

A more compact expression for AR(p) can be obtained by utilizing the backshift operator. The symbol AR(p) will be used to denote a p^{th} order AR model

$$(1 - \phi_1 B - \phi_2 B^2 - . . . . - \phi_p B^p)z_t = a_t + \delta \qquad (8)$$

or

$$\phi(B)z_t = a_t + \delta$$

where

$$\phi(B) = (1 - \phi_1 B - \phi_2 B^2 - . . . . - \phi_p B^p)$$

For every finite order AR model it can be shown that there exists a corresponding infinite order MA model (Chatfield, 1975). The strategy for doing this will be illustrated for the case of an AR(1) model:

$$z_t = \phi_1 z_{t-1} + a_t + \delta \tag{9}$$

The term z_{t-1} can be eliminated from the AR(1) model by substituting

$$z_{t-1} = \phi_1 z_{t-2} + a_{t-1} + \delta$$

in Equation 4.19 to obtain

$$z_t = \phi_1^2 z_{t-2} + a_t + \phi_1 a_{t-1} + \delta(1 + \phi_1) \tag{10}$$

the term z_{t-2} can be eliminated by substituting

$$z_{t-2} = \phi_1 z_{t-3} + a_{t-2} + \delta$$

into Equation 4.20 to obtain

$$z_t = \phi_1^3 z_{t-3} + a_t + \phi_1 a_{t-1} + \phi_1^2 a_{t-2} + \delta(1 + \phi_1 + \phi_1^2)$$

Proceeding in this fashion yields

$$z_t = a_t + \sum_{i=1}^{\infty} \phi_1^i a_{t-i} + \frac{\delta}{1 - \phi_1} \tag{11}$$

which is an MA(∞) model in which

$$\theta_i = - \phi_1^i$$

$$\mu = \frac{\delta}{1 - \phi_1}$$

It can also be shown that for every finite order MA model there exists a corresponding infinite order AR model (Nelson, 1973). The strategy for doing this will be illustrated for the case of an MA(1) model

$$z_t = a_t - \theta_1 a_{t-1} + \mu \qquad (12)$$

The term a_{t-1} can be eliminated from an MA(1) model by substituting

$$z_{t-1} = a_{t-1} - \theta_1 a_{t-2} + \mu$$

in Equation 4.22 to obtain

$$z_t = a_t - \theta_1 z_{t-1} - \theta_1^2 a_{t-2} + \mu(1 + \theta_1)$$

Next the term a_{t-2} can be eliminated from an MA(1) model by substituting

$$z_{t-2} = a_{t-2} - \theta_1 a_{t-3} + \mu$$

to obtain

$$z_t = a_t - \theta_1 z_{t-1} - \theta_1^2 z_{t-2} - \theta_1^3 a_{t-3} + \mu(1 + \theta_1 + \theta_1^2)$$

Proceeding in this fashion yields

$$z_t = a_t - \sum_{i=1}^{\infty} \theta_1^i z_{t-i} + \frac{\mu}{1 - \theta_1} \qquad (13)$$

which is an AR(∞) model in which

$$\theta_i = \phi_1^i$$

$$\delta = \frac{\mu}{1 - \theta_1}$$

Thus, the MA model and the AR model represent alternative ways for describing a time series. In a particular situation the model which explains the situation with the smallest number of parameters will be preferred. The AR model will be better for situations in which the effect of a disturbance on future observations gradually dies out. The MA model will be better for situations in which the effect of a disturbance ends abruptly after a specified number of observations. In situations between these two extremes a mixed auto-regressive-moving average (ARMA) model will provide the simplest explanation.

The general form of the ARMA process is given by

$$z_t = \phi_1 z_{t-1} + \ldots + \phi_p z_{t-p} + \delta + a_t - \theta_1 a_{t-1} - \ldots - \theta_q a_{t-q} \tag{14}$$

where

z_i = i^{th} value of the observed time series

a_t = i^{th} value of the disturbance

δ = mean of the ARMA process

ARMA(p,q) will be used to denote an ARMA model with p autoregressive and q moving average terms. The backshift operator can be used to obtain a more compact expression for the ARMA model

$$\phi(B) z_t = \theta(B) a_t + \delta \tag{15}$$

or

$$z_t = \frac{\theta(B)}{\phi(B)} a_t + \delta$$

where

$$\phi(B) = (1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)$$

$$\theta(B) = (1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q)$$

Through the use of an ARMA model it is often possible to describe a time series with fewer parameters than would be the case if either an AR model or an MA model were used alone. However, it also includes both the AR and MA models as special cases. It, therefore, represents the most general model for describing a nonseasonal stationary time series. However, most economic time series are both seasonal and nonstationary.

The strategy for dealing with nonstationary time series is to transform the original data in a manner which will remove the nonstationarity. Differencing the original data represents the primary means for removing the aspect of nonstationarity caused by changes in the mean level of the process. In practice it is seldom necessary to go beyond the second difference. If w_t is defined as the sequence of first differences

$$w_t = z_t - z_{t-1} \tag{16}$$

then the ARMA model applied to the differenced data becomes:

$$w_t = \phi_1 w_{t-1} + \ldots + \phi_p w_{t-p} + a_t + \theta_1 a_{t-1} - \ldots - \theta_q a_{t-q} \tag{17}$$

Note that the process of taking the first difference eliminates the constant term δ from the ARMA model given by Equation 14. The backward shift operator B can be used to obtain a more compact expression for Equation 17

$$\phi(B)\ (1 - B)^d z_t = \theta(B) a_t \tag{18}$$

where d represents the level of differencing required to remove the nonstationarity and the remaining terms have been defined previously. The model in Equation 18 describes the change in the level of the time series. The level at any given time will be equal to the sum of all past changes. Since summation is a discrete counterpart of integration the model in Equation 18 is referred to as integrated autoregressive-moving average (ARIMA) model. An ARIMA model in which an ARMA(p,q) model is used to describe the d^{th} difference of the data is referred to by ARIMA(p,d,q).

In economic time series, nonstationarity often arises from a tendency of the variance of a time series to increase over time. This source of nonstationarity can often be removed by working with logs of the original data.

The seasonality encountered in economic time series is usually multiplicative in nature. To cope with multiplicative seasonality Box and Jenkins recommended using the following model:

$$\phi(B)(1 - B)^d \Phi(B)(1 - B^s)^D z_t = \theta(B)\Theta(B^s)a_t \tag{19}$$

where

s = period of seasonality

$\phi(B) = (1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)$ = nonseasonal AR operator

$\Phi(B) = (1 - \Phi_1 B^s - \Phi_2 B^{2s} - \ldots - \Phi_P B^P)$ = seasonal AR operator

$\theta(B) = (1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q)$ = nonseasonal MA operator

$\Theta(B) = (1 - \Theta_1 B^s - \Theta_2 B^{2s} - \ldots - \Theta_Q B^Q)$ = seasonal MA operator

d = order of nonseasonal differencing

D = order of seasonal differencing

$(1 - B)^d$ = nonseasonal difference operator

$(1 - B^s)^D$ = seasonal difference operator.

The symbol ARIMA(p,P,d,D,q,Q) will be used to represent the model described by Equation 19.

The ARIMA(p,P,d,D,q,Q) model encompasses most forecasting models as special cases. These special cases include the following forecasting methods: (a) single exponential smoothing; (b) double exponential smoothing; (c) triple exponential smoothing; (d) Winters method; (e) adaptive smoothing; and (f) X-11 variant of the Census Method II Seasonal Adjustment Program developed by the United States Bureau of the Census.

The flow chart in Figure 9 provides an overview of the process used to determine which model within the ARIMA(p,P,d,D,q,Q) family is best for forecasting the behavior of a particular time series.

Identification. The identification process is concerned with tentatively selecting a model from the ARIMA(p,P,d,D,q,Q) family of models. This involves specifying values for p, P, d, D, q, and Q. The first step is to determine whether or not the series is stationary. A rough idea as to whether or not a particular series is stationary can be obtained by examining a plot of the raw data. Nonstationarity will be evidenced by changes in the mean and/or variance of the process over time. Trends will also indicate nonstationarity. The acf can also be used to determine whether or not a time series is stationary. If a series is nonstationary the autocorrelations will die out slowly (Box & Jenkins, 1970, p. 174-175; 200-201). The nonstationarity which exists

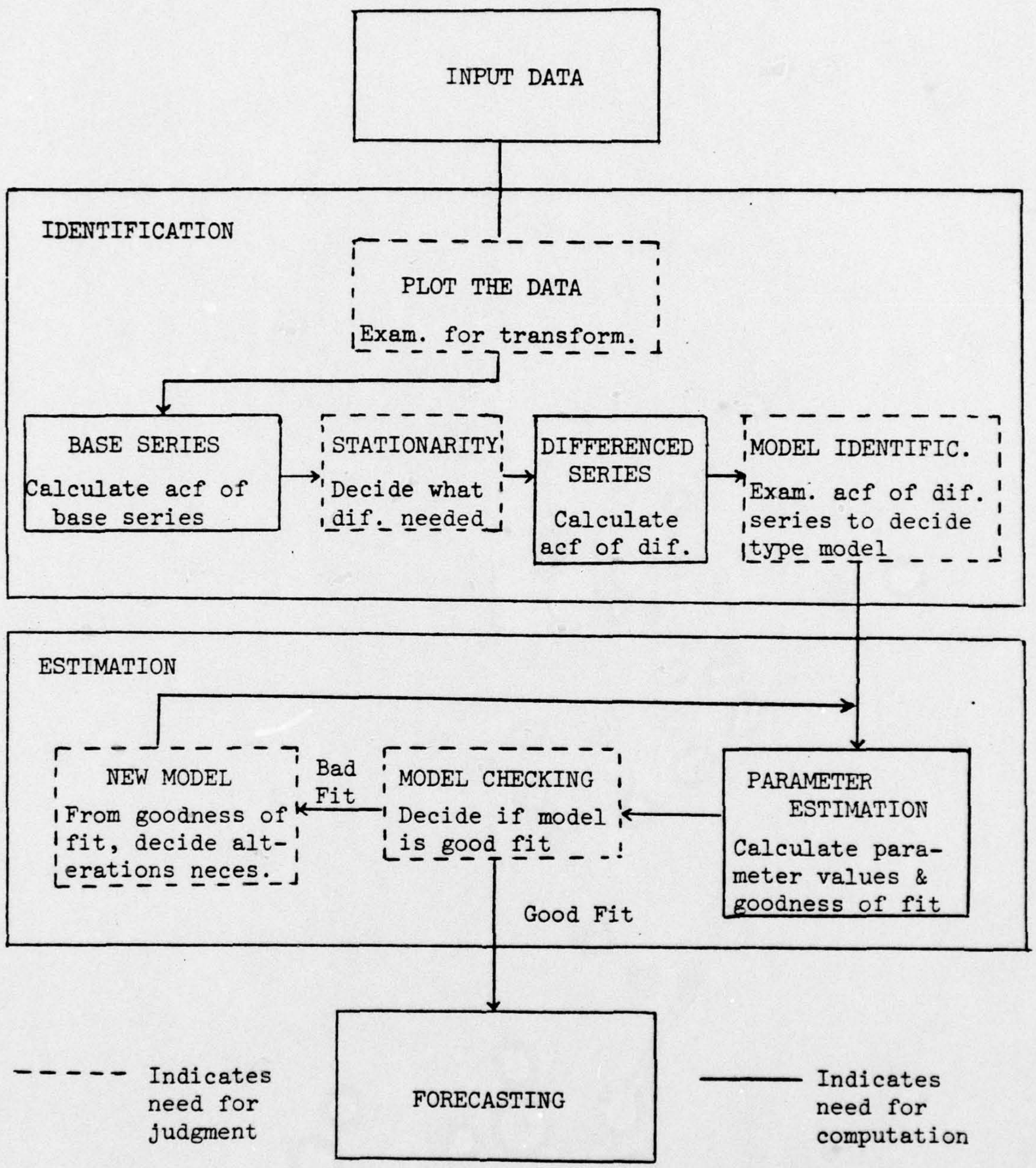


Figure 14. Flow Chart of the Process for Determining the Specific Model within the ARIMA(p,P,d,D,q,Q) Family of Models

in a series can be either seasonal or nonseasonal or both, ie:

1. Nonseasonal nonstationarity is evidenced when the autocorrelations at successive lags die out slowly as in Figure 15.
2. Seasonal nonstationarity is evidenced when there is a cyclic pattern in the autocorrelations as in Figure 16.
3. Seasonal nonstationarity is also evidenced when the autocorrelations separated by the seasonal period die out slowly as in Figure 17.
4. Both seasonal and nonseasonal nonstationarity are evidenced when 1 and either 2 or 3 occur.

Nonstationarity can be reduced by differencing the original data. There are two basic types of differences: (a) nonseasonal differences which are obtained by subtracting observations separated by one time period; and (b) seasonal differences which are obtained by subtracting observations separated by the length of the seasonal period.

It is very important to correctly identify the orders of the nonseasonal differences and the seasonal differences. Undifferencing leaves dependencies in the data which should be removed, while overdifferencing introduces dependencies in the data which should not be there. The following can be used as guidelines for identifying the proper orders of nonseasonal and seasonal differences:

1. The variance for a correctly differenced series will be lower than the variances for the series which have been either overdifferenced or underdifferenced.
2. The value of the Box-Pierce (1970) test statistic

$$Q = T \sum_{j=1}^{k} r_j^2 (\hat{a})$$

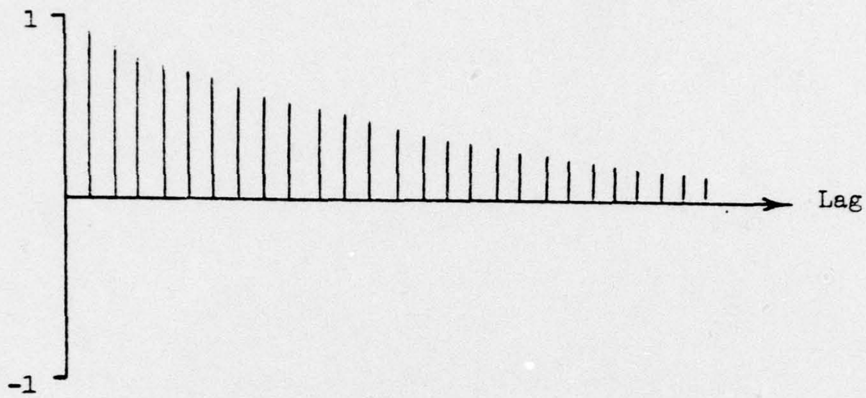


Figure 15. Autocorrelation Function for Nonseasonal Nonstationary Time Series

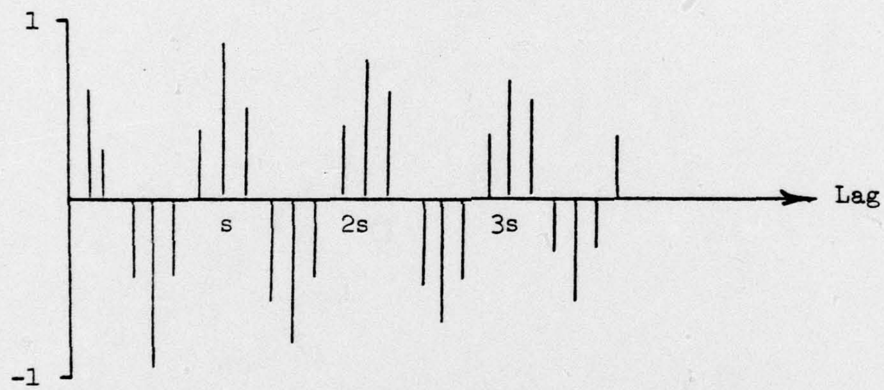


Figure 16. Autocorrelation Function for Seasonal Nonstationary Time Series

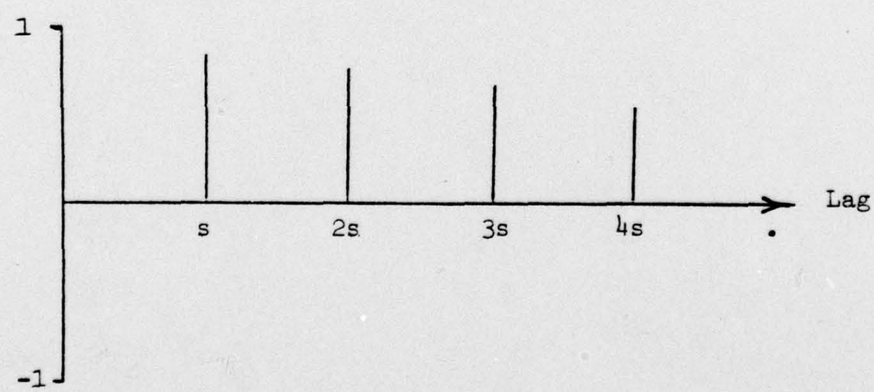


Figure 17. Autocorrelation Function for Seasonal Nonstationary Time Series

UNCLASSIFIED

ØØ ØØ AØ77331 (U) FIELD/GROUP ØØØØØØ

UNCLASSIFIED TITLE

ANALYSIS OF THE COST OF VARIABLE WORKLOADS ON SHIPBUILDING.

ABSTRACT

(U) THE EFFECT OF SHIPYARD WORKLOAD VARIATION ON THE COST OF BUILDING SHI
ORTS ARE PRESENTED. THE FIRST MAJOR EFFORT CONSISTS OF AN ANALYSIS OF THE
ON SHIPBUILDING PRODUCTIVITY AND COST. THE RESULTS SHOW THAN AN OPTIMUM
VEL EXIST AS A RESULT OF A TRADEOFF BETWEEN WORK DENSITY EFFECTS AND FIXE
DENTIFY CAUSES OF SHIPYARD PRODUCTIVITY VARIATION BASED ON INTERVIEWS WIT
FORT INVOLVED DEVELOPMENT OF A FRAMEWORK FOR ESTIMATING TRANSFER FUNCTION
OST. THIS WORK IS TO BE BASED ON HISTORICAL PRODUCTON AND COST DATA.A DES
NG METHODOLOGY TO THE PROBLEMIS PRESENTED. THE FOURTH EFFORT CONCERNS DEV
IZE COST OF ADJUSTING TO WORKLOAD VARIATIONS. A REVIEW OF CURRENT APPROAC
ODELS IS GIVEN ALONG WITH A PROPOSED DECOMPOSTION OF THE PLANNING PROBLEM
TRATEGIC OR LONG-RANGE MANPOWER PLANNING AND FACILITES EXPANSION. THE TAC
WORKFORCE ALLOCATION ON A TRADE LEVEL TO THE VARIOUS ACTIVITIES COMPOSING
LANNING LEVEL IS SHORT-TERM DETAILED PLANNING THAT TAKES INTO ACCOUNT INT
T RELATIONSHIPS (PROPERSEQUENCING) FOR EACH TASK AND MANPOWER ALLOCATION.

INDEX TERMS ASSIGNED

COSTS	COSTS
ALLOCATIONS	MANPOWER
MANAGEMENT PLANNING AND CONTROL	SHIPBUILDING
TRANSFER FUNCTIONS	JOB ANALYSIS

TERMS NOT FOUND ON NLDB

BOX-JECKINS FORECASTING METHODOLOGY	BUILDING SHIP
INTER-AND INTRA-TRADE	LONG-RANGE MA
MULTI-RESOURCE MULTI-PROJECT	OPTIMUM LEAST
SHIPBUILDING PRODUCTIVITY	SHIPYARD PLAN
SHIPYARD PRODUCTIVITY	SHIPYARD SUPE
SHIPYARD WORKLOAD	STRATEGIC COM
STRATEGIC MANPOWER PLANNING	TACTICAL COMP
TACTICAL COMPONENTS	TACTICAL PLAN
TRADE LEVEL	VARIABLE WORK
WORK DENSITY	WORK DENSITY
WORKLOAD VARIATIONS	WORK-FORCE LE

UNCLASSIFIED

)a

ON SHIPBUILDING.

TION ON THE COST OF BUILDING SHIPS HAS BEEN ANALYZED. THE RESULTS OF FOUR EFF
CONSISTS OF AN ANALYSIS OF THE EFFECT OF WORK DENSITY (I.E. WORKER CROWDING)
E RESULTS SHOW THAN AN OPTIMUM LEAST COST CONSTRUCTION TIME AND WORK-FORCE LE
N WORK DENSITY EFFECTS AND FIXED COSTS. THE SECOND EFFORT WAS AN ATTEMPT TO I
RIATION BASED ON INTERVIEWS WITH SHIPYARD SUPERVISORY PERSONNEL. THE THIRD EF
OR ESTIMATING TRANSFER FUNCTIONS TO DESCRIBE HOW WORKLOAD VARIATION AFFECTS C
L PRODUCTON AND COST DATA.A DESCRIPTION OF ADAPTING THE BOX-JECKINS FORECASTI
THE FOURTH EFFORT CONCERNS DEVELOPMENT OF A SHIPYARD PLANNING SYSTEMTO MINIM
NS. A REVIEW OF CURRENT APPROACHES TO MULTI-RESOURCE/MULTI-PROJECT PALNNING M
POSTION OF THE PLANNING PROBLEM INTO STRATEGIC AND TACTICAL COMPONENTS. THE S
ND FACILITES EXPANSION. THE TACTICAL COMPONENT IS MORE DETAILED AND INVOLVES
HE VARIOUS ACTIVITIES COMPOSING THE CONSTRUCTION OF EACH SHIP. THE TACTICAL P
ING THAT TAKES INTO ACCOUNT INTER-AND INTRA-TRADE INTERFERENCES, PRECEDENCE A
H TASK AND MANPOWER ALLOCATION. (AUTHOR)

INDEX TERMS ASSIGNED
- COSTS
- MANPOWER
- SHIPBUILDING
- JOB ANALYSIS

TERMS NOT FOUND ON NLDB
- BUILDING SHIPS
- LONG-RANGE MANPOWER PLANNING
- OPTIMUM LEAST COST CONSTRUCTION TIME
- SHIPYARD PLANNING
- SHIPYARD SUPERVISORY PERSONNEL
- STRATEGIC COMPONENTS
- TACTICAL COMPONENT
- TACTICAL PLANNING LEVEL
- VARIABLE WORKLOADS
- WORK DENSITY EFFECTS
- WORK-FORCE LEVEL

where

T = total number of observations minus the maximum order of differencing

K = number of values of sample acf that have been calculated

$r_j^2(\hat{a})$ = sample acf of the difference time series will be smaller for the correctly differenced series than the values associated with series that have been either overdifferenced or underdifferenced.

The next step in the identification process after obtaining a stationary time series is to determine the orders of the nonseasonal and seasonal autoregressive and moving average operators. This will be accomplished by comparing the shapes of the sample acf and pacf with the shapes of the theoretical acf's and pacf's corresponding to the various models in the ARIMA(p, P, d, D, q, Q) family of models. The model whose theoretical acf and pacf best match the shapes of the sample acf and pacf will be tentatively selected as the model to be fitted to the observed data.

Since in practice it is seldom necessary for any of the operators in the ARIMA(p,P,d,D,q,Q) model to be higher than the second order, Box and Jenkins (1970, Chapter 3) have analyzed the shapes of the theoretical acf's and pacf's for these models. This analysis provided the basis

for constructing the charts in Appendix A. These charts can be used to facilitate the process of determining the tentative orders for the nonseasonal and seasonal autoregressive and moving average operators. These charts should be used as follows:

1. For nonseasonal models compare the shape of the estimated acf of the stationary series with the shapes of the theoretical acf's shown in the charts and select the model (or models) whose theoretical acf best matches the shape of the sample acf.

2. For a model which is completely seasonal ignore the values of the sample acf at lags which do not correspond with the seasonal period and then determine the model whose theoretical acf best matches the shape of the relevant portions of the sample acf.

3. For a model which has both seasonal and nonseasonal operators: (a) Disregard the significant seasonal correlations in the sample acf and apply step 1 to the relevant portion of the sample acf. (b) Disregard the significant nonseasonal correlations in the sample acf and apply step 2 to the relevant portion of the sample acf.

The process for determining the tentative orders for the seasonal and nonseasonal autoregressive and moving average operators places primary emphasis on matching the sample acf with the theoretical acf corresponding to one of the ARIMA(p,P,d,D,q,Q) models. If acf's of two or more of these models appear to match a sample acf equally well, then the pacf's should be compared to determine which is most appropriate.

The reason for placing primary emphasis on the acf is that the procedure for estimating the pacf "becomes very sensitive to rounding errors and should not be used if the values of the parameters are close to the nonstationary boundaries" (Box and Jenkins, 1970, p. 65).

The autocorrelations calculated from the stationary time series are only estimates of the actual correlations and are therefore subject to sampling error. To test the significance of an individual autocorrelation coefficient Box and Jenkins (1970, p. 34-35) recommended using an approximate expression for the variance of the autocorrelation coefficient developed by Bartlett (1946),

$$V(r_j) \approx \frac{1}{N} \{1 + 2 \sum_{i=1}^{q} \rho_i^2\}$$

where

N = number of observations in stationary time series

r_j = sample estimate of autocorrelation coefficient for a pair of observations separated by j periods

ρ_i = theoretical autocorrelation coefficient for a pair of observations separated by i periods

$V(r_j)$ = variance of r_j

q = separation beyond which theoretical autocorrelation coefficients are zero

If the mean of a stationary time series is significantly different from zero, then it will be necessary to add a constant term to the ARIMA(p,P,d,D,q,Q). This situation will arise when there is a persistent trend in the undifferenced time series.

Estimation. Once the tentative form of the model has been decided upon the next step is to estimate the parameter values in the model.

The least squares criterion is used to determine the best estimates of the parameters of the ARIMA(p,P,d,D,q,Q) and their standard deviations. When the a_t's are Normally distributed the least squares estimators of

$$\phi = (\phi_1, \phi_2, \ldots, \phi_p)$$
$$\Phi = (\Phi_1, \Phi_2, \ldots, \Phi_P)$$
$$\theta = (\theta_1, \theta_2, \ldots, \theta_q)$$
$$\Theta = (\Theta_1, \Theta_2, \ldots, \Theta_Q)$$

in the ARIMA(p,P,d,D,q,Q) model

$$\phi(B)(1 - B)^d \Phi (B)(1 - B^s)^D z_t = \theta(B)\Theta (B^s)a_t \tag{20}$$

where

s = period of seasonality

$\phi(B) = (1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)$ = nonseasonal AR operator

$\Phi(B) = (1 - \Phi_1 B^s - \Phi_2 B^{2s} - \ldots - \Phi_P B^P)$ = seasonal AR operator

$\theta(B) = (1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q)$ = nonseasonal MA operator

$\Theta(B) = (1 - \Theta_1 B^s - \Theta_2 B^{2s} - \ldots - \Theta_Q B^Q)$ = seasonal MA operator

d = order of nonseasonal differencing

D = order of seasonal differencing

$(1-B)^d$ = nonseasonal difference operator

$(1-B^s)^D$ = seasonal difference operator

will closely approximate the maximum likelihood estimates of these parameters.

The expression for a_t is obtained by rewriting Equation 20 as follows:

$$a_t = \theta^{-1}(B)\Theta^{-1}(B)\phi(B)\Phi(B)(1 - B)^d(1 - B^s)^D z_t \tag{21}$$

Note that a_t is a nonlinear function of the parameters of the ARIMA(p,P, d,D,q,Q) model. Hill climbing techniques are used to determine the parameter values which minimize the sum of squares.

The computational effort required to solve this nonlinear least squares problem can be reduced by starting the search procedure at parameter values which are close to their true values. Table 1 summarizes the procedure for obtaining preliminary estimates of the parameters for nonseasonal models.

Diagnostic testing. The adequacy of a model will be indicated when the following conditions are satisfied: (a) the residuals are not significantly different from white noise; and (b) all of the parameters of the model are significantly different from zero.

Box and Pierce (1970) have developed a test for determining whether or not a sample acf is significantly different from white noise. This test utilizes the following test statistic

$$Q = T \sum_{j=1}^{K} r_j^2(\hat{a})$$

where

T = total number of observations minus the maximum order of differencing

K = number of values of sample acf that have been calculated

$r_j^2(\hat{a})$ = sample acf of the estimated residual series.

TABLE 1

Summary of Procedures for Obtaining Preliminary Estimates of the Parameters of Nonseasonal Models

p	d	q	Preliminary estimate of parameter
1	any positive integer	0	$\phi_1 = \rho_1$ subject to $-1 < \phi_1 < 1$
0	any positive integer	1	See Table A, p. 517-518, in Box and Jenkins (1970) to obtain estimate of θ_1.
2	any positive integer	0	See Chart B, p. 518, in Box and Jenkins (1970) to obtain estimates of ϕ_1 and ϕ_2.
0	any positive integer	2	See Chart C, p. 519, in Box and Jenkins (1970) to obtain estimates of θ_1 and θ_2.
1	any positive integer	1	See Chart D, p. 520, in Box and Jenkins (1970) to obtain estimates of ϕ_1 and θ_1.
any positive integer	any positive integer	any positive integer	See Appendix A6.2, p. 201-205, in Box and Jenkins (1970).

Q is approximately chi-square distributed with K-p-q degrees of freedom where p and q represent the number of autoregressive and moving average parameters in the model under consideration.

If the above test indicates that the residual series is significantly different from white noise, then the sample acf of the residuals should be analyzed to determine how the model should be improved

Another means of assessing the adequacy of the fitted model is to test the significance of the individual terms in the sample acf. This test is based on the fact that the distribution of the estimated autocorrelations of residuals is approximately Normal with mean zero and variance equal to the reciprical of the sample size (Box & Jenkins, 1970, p. 290).

Using more parameters in a model than necessary is referred to as overfitting. This should be avoided since the presence of the unnecessary parameters will probably bias the estimates of the essential parameters. Unnecessary parameters will be indicated by the fact that the $1 - \alpha$ confidence limits for the parameter estimate include the value zero (The procedure for establishing these confidence limits is described in Box and Jenkins (1970, p. 224-231).).

An Overview of the Box-Jenkins Transfer Function Model

The Box-Jenkins univariate method utilizes only the historical values of a time series in forecasting future behavior. Often there will exist one or more variables which influence the behavior of the variable being forecast. These causal variables have the potential for increasing forecast accuracy. To exploit this potential Box and Jenkins

(1970) developed a process for building forecasting models which utilizes both the historical values of the series being forecast and leading variables to forecast future behavior. This model building process is referred to as the transfer function method.

The transfer function model visualizes the leading variables as inputs to a process which produce the variable being forecast as an output. The objective of the transfer function model is not to discover a model which describes in great detail the causal mechanism whereby the input is transformed into the output. Instead, the transfer function model regards the transformation as a black box and seeks only to discover which of a large family of mathematical models best describe how a change in the input affects the output over time. The function which describes how the input, during a particular period, affects the output during future time periods is referred to as the impulse response function.

The impulse response functions found in practice take on a wide variety of shapes. Some will follow an oscillatory pattern while others will be oscillation-free. For those following an oscillatory pattern some will follow a damped sine wave pattern while others will follow a pattern in which the effects in successive periods will alternate in sign. For those that are oscillation-free some will be unimodal while others will be monotone. In some situations the effects will decay

gradually over time. In other situations the effects will persist for a period of time and then end abruptly. The delay between the change in the input and its affect on the output will vary from one situation to another. The variety of possible shapes which the input response function can take on in practice necessitates that the family of mathematical models from which the theoretical impulse response is selected must be extremely flexible. The required flexibility can be found in a model of the type:

$$\delta(B)y_t = \omega(B)B^b x_t \tag{22}$$

where

x_t = input

y_t = output

B = backshift operator

b = delay

$\delta(B) = (1 - \delta_1 B - \ldots - \delta_r B^r)$ = output lag operator

$\omega(B) = (\omega_0 - \omega_1 B - \ldots - \omega_s B^s)$ = input lag operator

This model can be rewritten as

$$y_t = \delta(B)x_{t-b} \tag{23}$$

where

$$\delta(B) = \frac{\omega(B)}{\delta(B)} = (\delta_0 + \delta_1 B + \delta_2 B^2 + \ldots)$$

The polynomial operator $\nu(B)$ represents the transfer function which summarizes the dynamic structure of the effect transferred from the input sequence to the output sequence. The values $\nu_0, \nu_1, \nu_2, \ldots$ represent the changes in output expected from a one-time-only unit change in input and are referred to as the impulse response coefficients. The only restriction on $\nu(B)$ is that if the input is held at a fixed level χ_f then the output eventually should settle at an equilibrium level y_e. This requirement often is not fulfilled by the data in the original form because of trends and seasonality. Fortunately, such problems can often be removed by appropriately differencing the data. The input lag operator $\omega(B)$ describes the magnitude of the more immediate effects of the input. The output lag operator describes the duration and pattern of decay for these effects.

Identification. The process for tentatively identifying the transfer function makes use of the cross correlation function (ccf) which measures the degree of association between the present value of a given time series variable and past, present, and future values of another time-series variable. The ccf is defined as

$$\rho_{xy}(k) = \frac{\gamma_{xy}(k)}{\sigma_x \sigma_y}$$

where

$\rho_{xy}(k)$ = cross correlation between x and y at lag k

$\gamma_{xy}(k)$ = cross covariance between x and y at lag k

σ_x = standard deviation of x

σ_y = standard deviation of y

The procedure is to, first, estimate the sample ccf for the observed data and then to find a theoretical transfer function model whose ccf closely matches the shape of the sample ccf. However, the sample ccf can not be estimated directly from the input and output series if the input series is highly autocorrelated. This results from the fact that autocorrelation in the input series induces autocorrelation in the ccf. This will distort the shape of the sample ccf which will make it more difficult to correctly identify the transfer function. Fortunately, this problem can be circumvented by reducing the input series to white noise. This can be accomplished by utilizing the Box-Jenkins univariate model described in the preceding section to fit an autoregressive integrated moving average (ARIMA) model to the input series. The process of reducing the input series to white noise is referred to as prewhitening the input. In order to preserve the relationship between input and output it will be necessary to apply the same model to the output series.

The result of this operation is referred to as the prewhitened output series. Since the same transformation is applied to both the input and output series, the transfer function model which fits the prewhitened series will also fit the original series.

Box and Jenkins (1970, p. 347-353) recommend the following procedure for using the sample ccf to tentatively identify the transfer function model:

1. The value of b, the delay, will be equal to the number of lags before the first non-zero cross correlation coefficient is encountered.

2. The value of r will be determined by the type pattern followed by the remaining values

$$r = \begin{cases} 0 & \text{if there are no values following a pattern} \\ 1 & \text{if the remaining values decay exponentially} \\ 2 & \text{if the remaining values follow a damped sine wave.} \end{cases}$$

3. The value of s can be obtained as follows:

$$s = \begin{cases} bp - (b + 1) \quad \text{for } np \geq 1 & \text{for } r \geq 1 \\ np - 1 & r = 0 \end{cases}$$

where

bp = number of values up to and including the value at which the pattern begins

np = number of values not following a pattern

In practice the input will almost always be able to explain only a portion of the variation in output. The inability of the input to fully account for all of the variation in output results from the presence of measurement errors and the influence of other causal variables. The residual series

$$n_t = y_t - \hat{V}(B)x_{t-b}$$

where

$\hat{V}(B)$ = preliminary estimate of transfer function

is used to estimate the noise series. The Box-Jenkins univariate model is then used to develop an ARIMA model for the noise series

$$\phi(B)(1 - B)^d n_t = \theta(B)a_t$$

or

$$n_t = \frac{\theta(B)}{(1 - B)^d \phi(B)} a_t$$

Thus the combined transfer function-noise model is

$$y_t = \frac{\omega(B)}{\delta(B)} B^b x_t + \frac{\theta(B)}{(1 - B)^d \phi(B)} \cdot a_t$$

The process for identifying a transfer function noise model is shown in the flow chart in Figure 14.

Estimation. Once the tentative forms of the transfer function and the noise model have been determined, the next step is to simultaneously estimate all of the parameters in the combined model

$$y_t = \frac{\omega(B)}{\delta(B)} B^b x_t + \frac{\theta(B)}{(1 - B)^d \phi(B)} a_t$$

where

$\delta(B) = (1 - \delta_1 B - \ldots - \delta_r B^r)$ = output lag operator

$\omega(B) = (\omega_0 - \omega_1 B - \ldots - \omega_s B^s)$ = input lag operator

$\phi(B) = (1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)$ = nonseasonal AR operator

$\theta(B) = (1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q)$ = nonseasonal MA operator

d = order of nonseasonal differencing

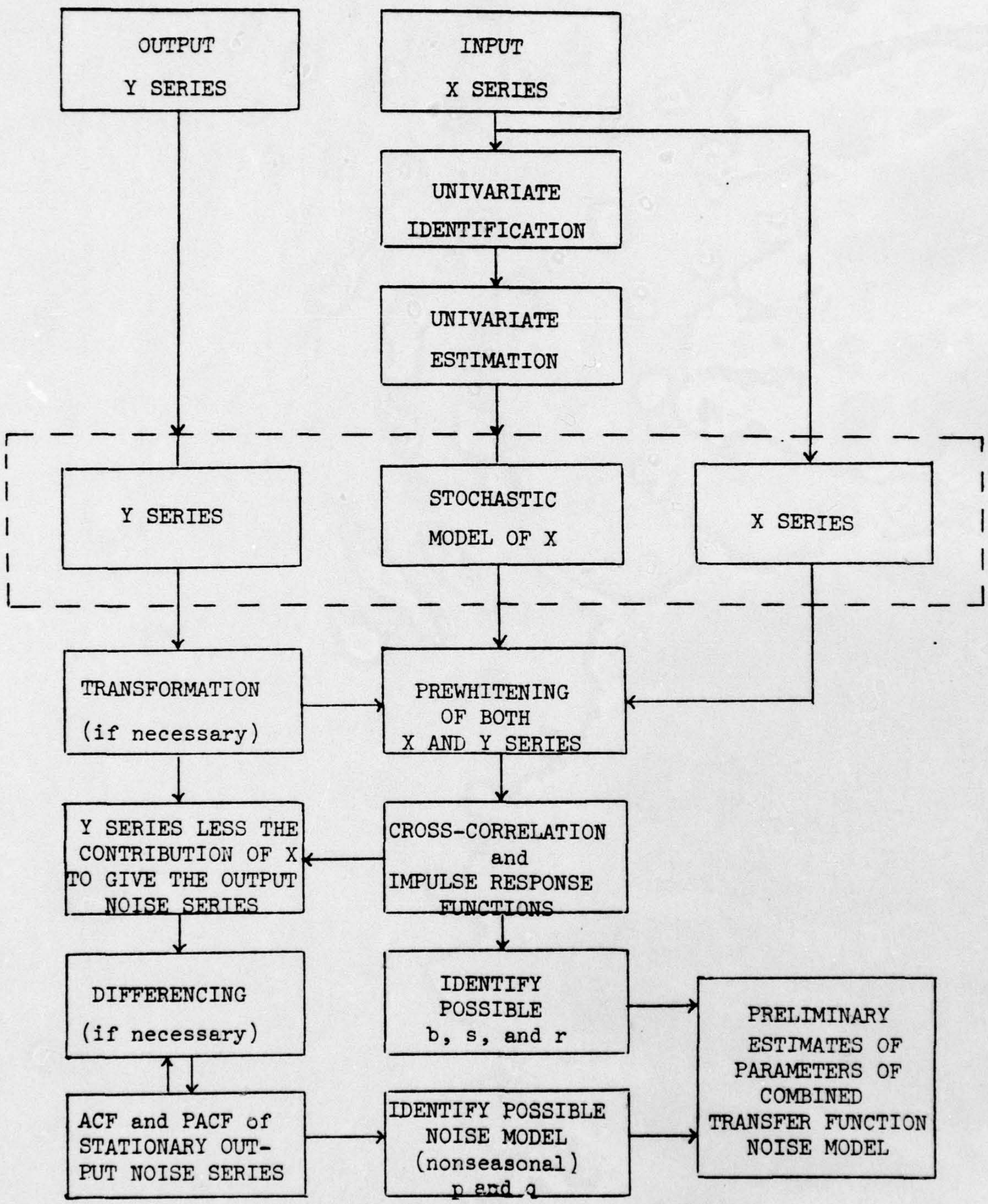


Figure 14. Flow Chart for the Process of Identifying the Transfer Function Noise Model

$(1-B)^d$ = nonseasonal difference operator

b = delay

The least squares criterion is used to determine the best estimates of the parameters of the combined model and their standard deviations. For the case when the a_t's are Normally distributed, the least squares estimators of

$$\omega = (\omega_0, \omega_1, \ldots, \omega_s)$$

$$\delta = (\delta_1, \delta_2, \ldots, \delta_r)$$

$$\phi = (\phi_1, \phi_2, \ldots, \phi_p)$$

$$\theta = (\theta_1, \theta_2, \ldots, \theta_q)$$

in the combined model will closely approximate the maximum likelihood estimators of these parameters (Box & Jenkins, 1970, p. 388).

The values of the a_t are estimated by the following three stage process:

1. The estimated output, $\hat{y}_t$, from the transfer function model is obtained by solving Equation 22 for y_t and then substituting the actual input, x_t, into the resulting expression

$$\hat{y}_t = \delta^{-1}(B)\omega(B)B^b x_t$$

2. The noise series, n_t, represents the difference between the estimated output and the actual output

$$n_t = y_t - \hat{y}_t$$

3. The values of the a_t series are obtained by solving the noise model for a_t and then passing the n_t series through the resulting expression

$$a_t = \frac{(1 - B)^d \phi(B)}{\theta(B)}$$

Note that a_t is a nonlinear function of the parameters of the transfer function and noise models.

Hill climbing techniques are used to determine the values of the parameters in the combined transfer function noise model which minimize the sum of squares. The computational effort required to solve this non-linear least squares problem can be reduced by starting the search procedure at parameter values which are close to their true values. Box and Jenkins (1970, p. 378-380) developed a procedure for obtaining preliminary estimates of the parameters of the transfer function. These should be used in conjunction with their procedures for obtaining preliminary estimates of the parameters of the noise model which are summarized

Diagnostic testing. The process for assessing the adequacy of the model utilizes both the acf of the estimated residuals and the ccf where the prewhitened input series is lagged relative to the estimated residual series. When the acf of the estimated residuals differs significantly from that of white noise, a problem in the noise model is indicated. A ccf which differs significantly from that which would be obtained when two white noise series are cross correlated indicates that the transfer function model is deficient.

The procedure for determining whether or not the acf differs significantly from white noise has already been described

in connection with diagnostic testing of a univariate model.

Box and Pierce (1970, p. 395) developed a test for determining whether or not a ccf differs significantly from that of two white noise series. This procedure utilizes the test statistic

$$Q = m \sum_{k=0}^{K} r^2_{\alpha\hat{a}}(k)$$

where

$m = n-u-p$

n = number of observations available for analysis

$u = \max \{r, s + b\}$

p = number of moving average terms in noise model

b = delay

r = number of output lag parameters

s = number of input lag parameters minus one.

Q is approximately chi-square distributed with $K+1-(r+s+1)$ degrees of freedom. If the above test indicates that the residual series is significantly cross correlated with the lagged values of the prewhitened input series, then the sample ccf should be used to determine how the model should be improved.

Box and Jenkins (1970, p. 394-395) also recommended testing the significance of the individual terms in the sample ccf as a means for determining whether or not a ccf differs significantly from that of two white noise series. This test is based on the assumption that the distribution of the estimated cross correlations is approximately Normal with mean zero and variance equal to the reciprocal of the sample size.

Using more parameters in a model than necessary is referred to as overfitting. This should be avoided since the presence of the unnecessary parameters will probably bias the estimates of the essential parameters. Unnecessary parameters will be indicated when the $1 - \alpha$ confidence limits for a parameter estimate includes the value zero (the procedure for establishing these confidence limits is described in Box and Jenkins, 1970, p. 391).

BIBLIOGRAPHY

Bartlett, M. S. On the theoretical specification of the sampling properties of autocorrelated time series. Journal of the Royal Statistical Society, 1946, B8, 27.

Bath Iron Works Corporation, Improved Planning and Production Control, A Report of Research Conducted Under MarAd Task 0-2 of the Ship Producibility Research Program To Determine The Value Of Engineered Standards In Planning And Production Control, Bath, Maine, August,

Bureau, Ansus, Current Industrial Reports, July 1970-June 1976.

Box, G. E. P. and Jenkins, G. M. Time series analysis forecasting and control. San Francisco: Holden-Day, 1970.

Box, G. E. P. and Pierce, D. A. Distribution of residual autocorrelations in autoregressive moving average time series models. Journal of the American Statistical Association, 1970, 64, 1509-1526.

Chatfield, C. The Analysis of Time Series: Theory and Practice. London: Chapman and Hall, 1975.

Chirillo, Louis D., personal communication, February, 1979.

Magnuson, Allen H. and Terry, William Robert, Work Density and Its Effect on Ship Construction Cost and Time,

Martin, John Charles, The Labor Market of the United States Shipbuilding Industry: 1960-1970, Ph.D. dissertation, George Washington University, June 1978, p. 23-25.

Nelson, C. R. Applied time series analysis for managerial forecasting. San Francisco: Holden-Day, Inc., 1973.

Pack, D. Computer programs for the analysis of univariate time series models and single input transfer function models using the methods of Box and Jenkins. Columbus, Ohio: The Ohio State University Data Center, Ohio State University, 1974.

Parker, Henry W. and Oglesby, Clarkson H., Methods Improvement for Construction Managers, McGraw-Hill Book Company, 1972.

Terry, William Robert, A Shipyard Planning System, July, 1979.

APPENDIX A

Theoretical Shapes of ACF's and PACF's

for Selected ARMA(p,q) Models

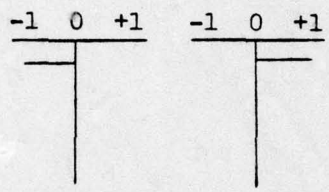
APPENDIX A

THEORETICAL SHAPES OF ACF's AND PACF's
FOR SELECTED ARMA(p,q) MODELS

Theoretical Autocorrelation Functions

(p=0, q=1)

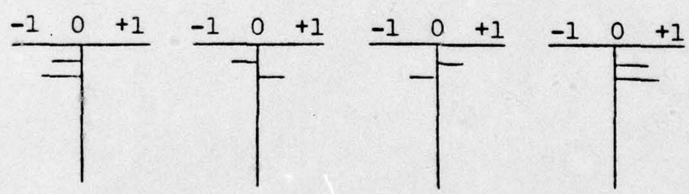
$\theta_1 > 0$ $\theta_1 < 0$



(p=0, q=2)

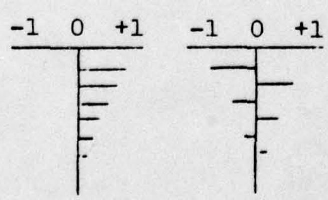
$\theta_1 > 0$ $\theta_1 > 0$ $\theta_1 < 0$ $\theta_1 < 0$

$\theta_2 > 0$ $\theta_2 < 0$ $\theta_2 > 0$ $\theta_2 < 0$



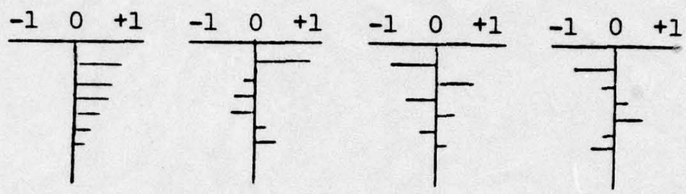
(p=1, q=0)

$\phi_1 > 0$ $\phi_1 < 0$



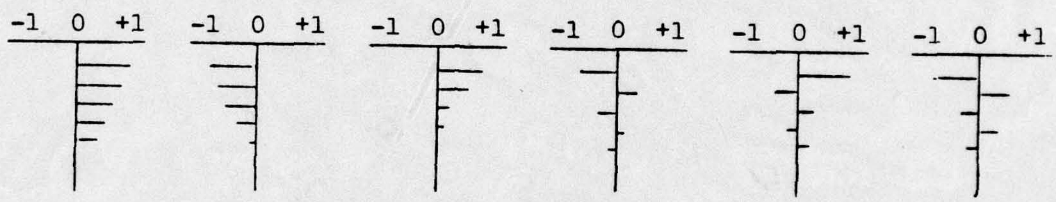
(p=2, q=0)

$\phi_1 > 0$ $\phi_2 > 0$ | $\phi_1 > 0$ $\phi_2 < 0$ | $\phi_1 < 0$ $\phi_2 > 0$ | $\phi_1 < 0$ $\phi_2 < 0$



(p=1, q=1)

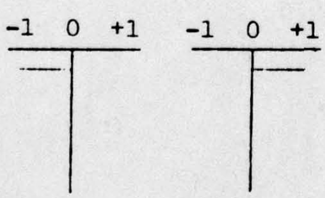
$\phi_1 > \theta_1 > 0$ | $\theta_1 > \phi_1 > 0$ | $\phi_1 > 0 > \theta_1$ | $\theta_1 > 0 > \phi_1$ | $0 > \phi_1 > \theta_1$ | $0 > \theta_1 > \phi_1$



<u>Theoretical Partial Autocorrelation Functions</u>

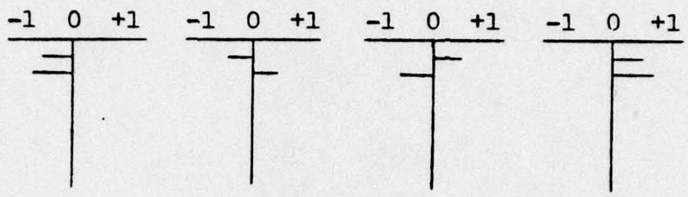
(p=1, q=0)

$\theta_1 < 0$ | $\theta_1 > 0$



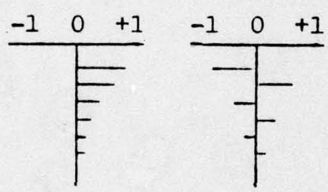
(p=2, q=0)

$\theta_1 < 0$, $\theta_2 < 0$ | $\theta_1 < 0$, $\theta_2 > 0$ | $\theta_1 > 0$, $\theta_2 < 0$ | $\theta_1 > 0$, $\theta_2 > 0$



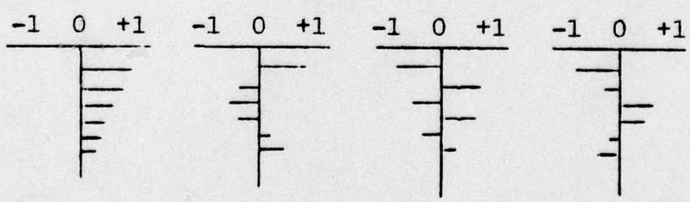
(p=0, q=1)

$\phi_1 < 0$ | $\phi_1 > 0$

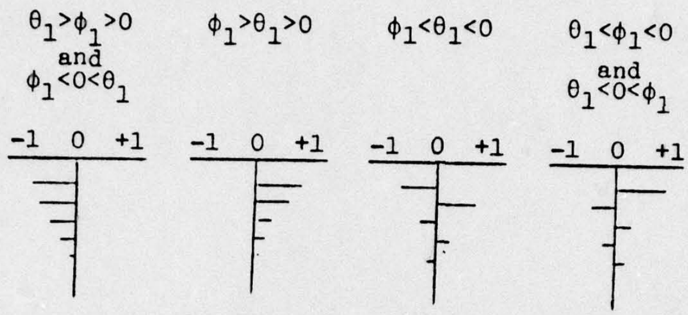


(p=0, q=2)

$\phi_1 < 0$, $\phi_2 < 0$ | $\phi_1 < 0$, $\phi_2 > 0$ | $\phi_1 > 0$, $\phi_2 < 0$ | $\phi_1 > 0$, $\phi_2 > 0$



(p=1, q=1)



$\theta_1>\phi_1>0$ and $\phi_1<0<\theta_1$
$\phi_1>\theta_1>0$
$\phi_1<\theta_1<0$
$\theta_1<\phi_1<0$ and $\theta_1<0<\phi_1$
-1 0 +1
-1 0 +1
-1 0 +1
-1 0 +1

APPENDIX D

A SHIPYARD PLANNING SYSTEM

by

William Robert Terry

July 5, 1979

Department of Industrial Engineering
and Operations Research

Virginia Polytechnic Institute and State University
Blacksburg, Virginia

PREFACE

The Industrial Engineering and Operations Research Department's activities were divided into three phases. The first phase, which is reported in "A Diagnosis of the Workload Variation Problem in Shipbuilding," was designed to identify specific problems for further analysis. This analysis revealed the need for the following:

(1) a system for analyzing how variations in shipyard workloads affect shipbuilding cost;

(2) a shipyard planning system which could be utilized by shipyards to minimize the cost of adjusting to workload variations.

Phase 2, which is described in "A Framework for Analyzing How Variations in Shipyard Workloads Impact Shipbuilding Cost," focused on developing the framework of a system for developing transfer function models which can be used to develop the difference equations which describe how variations in shipyard workloads affect shipbuilding cost. Phase 3, which is the subject of this report, focused on developing the framework of a shipyard planning system which shipyards could use to minimize the cost of adjusting to workload variations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

I. INTRODUCTION

Building a ship is a large scale endeavor which typically requires three or four years to complete. During this time the services of the construction trades listed in Table 1 will be used.

These trades will be responsible for producing, erecting, installing, assembling, and testing an enormous number of parts as indicated in Table 2.

Frisch (1976) observed that the most appropriate method for producing any of the above parts or assembling any number of them into subsystems will depend on the following factors: (1) the quantity of the item to be produced in a single run; (2) the weight of the items being produced or assembled; and (3) the complexity of the items or subsystem which is a function of the tolerances which must be maintained in production and/or assembly. He then defined seven different levels of complexity which are illustrated in Table 3. He then constructed a table (Table 4) to contrast the complexity of a ship with that of a watch and a car.

A wide variety of equipment will be used in performing the numerous tasks involved in constructing a ship. These tasks are typically classified into three categories: (1) hull construction; (2) outfitting; and (3) machinery installation. Table 5 shows the major processes involved in hull construction and the major types of equipment used during each process.

In addition there are numerous major items which are installed during outfitting. These are listed in Table 6.

The major items of equipment installed during machinery installation are listed in Table 7. Numerous types of specialized equipment will be

Table 1

CONSTRUCTION TRADES IN SHIPBUILDING

Automotive Operator (all types)	Machine Operator
Blacksmith	Machinist (inside-outside)
Boilermaker	Maintenance Man
Calker and Chipper	Material Chaser
Carpenter	Nuclear (all types)
Crane Operator (all types)	Painter (all types)
Diesel Mechanic	Pipe Coverer and Insulator
Electrician (inside-outside)	Pipefitter
Electronics Mechanic	Quality Control Technician
Engine Locomotive Operator (all types)	Rigger
Engine and Pump Operator	Sandblaster
Flame Cutter (Burner)	Sheetmetal Worker
Heat Treating Mechanic (Bulkhead Straightman)	Shipfitter
Hooker-on	Tractor Operator
Hydraulic Mechanic	Tool Clerk
Instrument Calibrator	Tool Repairman
Joiner	Ventilation Man
Laborer, Shipyard	Warehouse Man
Lead Burner	Welder
Loftsman	X-Ray Radiographer

Source: Mark Battle Associates, Inc., Shipbuilding Manpower Study: Executive Summary, March, 1974.

Table 2

NUMBER OF UNITS OR PIECES IN BUILDING A SHIP

	Number of Units or Pieces: 10,000 ton dwt cargo ship	Number of Units or Pieces: 60,000 ton dwt tanker	Number of Sizes or Classes of Items
Structural steel (cut pieces)	25,000	40,000	NA
Sheet steel (cut pieces)	1,500	2,500	NA
Sections of pipe	2,500	3,500	NA
Electric cable (various)	100,000	200,000	NA
Propulsion engines, other machinery units, motors, pumps, fans, etc.	200	350	NA
Various purchased material items	22,500	60,000	NA
Stock and supply items by sizes and types (bolts, nuts, stock fittings, pipe flanges, etc.)			1,500-2,500

Source: Mack-Forlist, Daniel M. and Arthur Newman, The Conversion of Shipbuilding From Military To Civilian Markets, Praeger Publishers, New York, 1970, p. 36.

Table 3

COMPLEXITY RATING -- EXAMPLES

PRODUCT TYPE	COMPLEXITY GROUP	ASSOCIATED TOLERANCE DESCRIPTION	PRODUCT EXAMPLES	
(1)	(2)	(3)	(4)	
Precision Products	1	EXTRA FINE	Precision Optical Instruments Navigation Instrumentation Optical Measuring Devices Research Electronics	Aircraft Instruments Measuring Equipment Watches Cameras
Industrial Products	2	FINE	Precision Power Tools Calculators and Adding Machines	Aircraft Engines Tape Recorders
	3	MEDIUM FINE	Automotive & Truck Engines Home & Industrial Power Tools Electronic Devices	Transmissions Differentials
	4	MEDIUM	Aircraft Construction (less instruments) Home Appliances Industrial Valves	Motors and Fans Power Lawn Mowers
	5	MEDIUM COARSE	Boat Building (Fiberglass molded) Loading & Handling Equipment Boilers & Heat Exchangers Agricultural Machinery	Earthmoving Equipment Anti-Pollution Devices Auto-Bodies
Construction Products	6	COARSE	Transmission Line Towers Shipbuilding (hull) Building Construction (all steel)	Bridge Construction Lock Gates Storage Tanks (steel)
	7	EXTRA COARSE	Masonry Bldg. Construction Water Irrigation Construction Dams & Protective Walls	Private Home Construction Highway Construction

Source: Frisch, F. A. P., "Production and Construction: A comparison of Concepts in Shipbuilding and Other Industries", Paper presented at the Fifth Annual DOD Procurement Research Conference, November 17-18, 1976, p. 60.

Table 4

COMPLEXITY COMPOSITION

COMPLEXITY GROUP	EXAMPLES		
	Watch[1]	Car[2]	Ship[3]
	Weight %	Weight %	Weight %
1 (EXTRA FINE)	92	1	1
2 (FINE)	8	5	2
3 (MEDIUM FINE)	--	45	13
4 (MEDIUM)	--	4	20
5 (MEDIUM COARSE)	--	45	15
6 (COARSE)	--	--	45
7 (EXTRA COARSE)	--	--	4

[1] MECHANICAL WRISTWATCHES

[2] PASSENGER CARS

[3] GENERAL CARGO SHIPS - COMMERCIAL

Source: Frisch, F. A. P., "Production and Construction: A Comparison of Concepts in Shipbuilding and Other Industries", Paper presented at the Fifth Annual DOD Procurement Research Conference, November 17-18, 1976, p. 62.

Table 5

HULL CONSTRUCTION

Process	Equipment
1. Receiving steel from mill and storing.	Railroad cars and/or lift trucks, trailers, tractors and cranes, possibly conveyors.
2. Blastcleaning or pickling.	Blastcleaning installation or pickling vats, railroad cars, lift trucks, tractors, trailers, cranes, conveyors.
3. Marking steel for cutting and for joining of stiffeners, etc.	Full-sized wooden and paper templates or scale (usually about 1-100), optical projection templates, tape-controlled marking equipment, conveyors, and manual tools and cranes.
4. Cutting steel.	Manual, semi-automatic, and automatic burning equipment, burning skids and cranes, possibly conveyors.
5. Punching for rivets (minor operation).	Multiple punches and drills, conveyors, cranes.
6. Cold forming.	Rolls, presses, and cranes.
7. Hot forming.	Furnaces, presses, forms, and jigs, hand tools, and cranes.
8. Intermediate storage.	Storage area, railroad cars, lift trucks, trailers, tractors, cranes, possibly conveyors.
9. Assembly precut parts.	Flat area (platens), some jigs, tack-welding equipment, joining brackets ("strong-backs", "saddles", etc.), burning equipment, welding equipment, possibly conveyors, cranes.
10. Intermediate storage.	Storage area, railroad cars, trailers, tractors, cranes.
11. Erection on ways.	Railroad cars, trailers, tractors, cranes, alignment tools, shores and supports, tack-welding equipment.
12. Completion on ways.	Shipfitters, tools, jacks, hoists, burning and welding equipment.
13. Launching.	Sliding ways and cradle, flooding equipment for building docks, cranes.
14. Completion of hull work at piers.	Welding and burning tools, jacks, hoists, cranes.

Source: Mack-Forlist, Daniel M. and Newman, Arthur, The Conversion of Shipbuilding from Civilian to Military Markets, Praeger Publishers, New York, 1970, pp. 38-39.

trades are incompatiable with one another. For example, none of the other trades can work in the area below welders. Another example, no trade can work in the same area as painters. Even if there are no precedence relationships between two or more work packages and work space is not a limiting factor, these work packages cannot be scheduled simultaneously if there is insufficient manpower.

The rates at which the various trades are used in constructing a given ship is not constant over time. During the early stages of construction, trades involved in constructing the hull, such as welders, shipfitters, riggers, loftsmen, hooker-on men, and flame cutters, will dominate the work force assigned to a given ship. During the latter stages of construction, trades involved with outfitting, such as electricians, pipefitters, sheetmetal workers, and carpenters, will dominate the workforce. The number of workers in each trade that will be needed during each scheduling period is difficult to determine. This results from the fact that "in ship construction, the model is the product and everything which cannot be predetermined with paper studies must be tried out during production in the form of rework, change orders, or something else" (Frisch, 1976, p. 40). This ad hoc approach to ship construction makes it virtually impossible to determine a priori all of the activities which will be necessary to construct a ship. Consequently, shipbuilders are not able to establish standard methods to the extent that this is done for products that are produced continuously or in large lot sizes. The lack of standard methods makes it difficult to develop accurate time standards which form the basis for estimating manpower requirements.

Nevertheless, not having the right number of workers in each trade during each time period can be extremely costly. If too few workers are assigned to a bottleneck activity, then the ship will not be completed on time. The penalty for not completing a ship on time consists of: (1) penalty payments for late delivery explicitly specified in the contract; and (2) opportunity cost. Typically, contracts for Navy ships do not explicitly contain late delivery penalty clauses. The opportunity cost for a 50 million dollar ship have been estimated to be at least \$20,000 per day (Corporate-Tech Planning, Inc., 1978). A shipyard will typically take one or more of the following actions when a planned delivery date is in jeopardy: (1) schedule overtime; (2) increase crew sizes; (3) postpone work until after launch; and (4) increase management involvement in day-to-day operation (Corporate-Tech Planning, Inc., 1978). On the other hand having too many workers would create idle time and increase labor cost unnecessarily.

Periodically wage rates for the various trades and cost of the various raw materials increase as a result of inflation. However, these rate and cost increases do not necessarily occur at the same time. The times at which these increases occur can be determined from union contracts for the various trades and by examining the times in the past at which previous price increases have occurred for the various raw materials. Note that the rate of increase for each of the trades and for each of the raw materials will not necessarily be the same. Under a fixed cost contract, inflationary trends provide an incentive to the shipyard to complete a ship as soon as possible. However, attempting to do this can result in intertrade and intratrade interferences.

TABLE 6

MAJOR ITEMS INSTALLED DURING OUTFITTING

1. Doors
   a. Watertight
   b. Non-watertight

2. Airports, port lights and windows

3. Manholes

4. Tonnage openings (optional)

5. Cargo hatch covers

6. Bulwarks

7. Cargo handling systems

8. Surface grating

9. Ladders

10. Anchors and anchor handling

11. Mooring lines

12. Lifting equipment

13. Sparrings

14. Deck covering

15. Insulation
   - Fire insulation
   - Sound insulation
   - Refrigeration insulation
   - Comfort insulation

16. Support wiring

17. Electrical wiring

18. Mooring and towing gears

19. Rudders

20. Steering gear and electrical equipment

TABLE 6 (continued)

21. Piping systems
    a. Bilge and ballast
    b. Fuel oil transfer
    c. Fresh water system
    d. Fire systems
       - sprinklers
       - CO_2 system, foam
    e. Cargo system
    f. Sanitary system

22. Ventilation systems
    a. Cargo hold ventilation and dehumidification
    b. Living and working area ventilation and dehumidification

23. Heating and air conditioning
    a. Cargo heating (typically for tankers)
    b. Living and working areas

24. Life saving equipment
    a. Life boats, rafts and floats
    b. Life boat mechanism and winches
    c. Life jackets

25. Navigation equipment
    a. Signal equipment
    b. Radio direction finder
    c. Navigation lights
    d. Sounding gear
    e. Compasses
    f. Radar
    g. Loran

26. Weapon systems (for combatant ships)

TABLE 7

MAJOR ITEMS OF EQUIPMENT INSTALLED DURING MACHINERY INSTALLATION

PRESERVATION AND MAINTENANCE

1. Painting
    a. Anti fouling marine coating
    b. Anti corrosion

2. Sanding

3. Blasting

PROPULSION MACHINERY

1. Steam turbine

2. Diesel

3. Reduction gears

4. Thrust bearing

5. Propeller shaft

6. Propeller

7. Crankshaft

AUXILIARY MACHINERY

1. Pumps

2. Boilers

3. Electric diesels and/or turbines

4. Evaporators

used by each of the many trades involved in outfitting and machinery installation.

From the above it is obvious that constructing a ship is an enormously complicated process which involves a staggering number of diverse activities. The activities for each trade are grouped in categories on the basis of geographic proximity. These categories are known as work packages. Typically the hull erection process and the outfitting process will be divided into approximately 2,500 work packages for each process. A typical work package requires approximately three months and 500 man-hours to complete (Corporate-Tech Planning, Inc., 1978).

These work packages cannot be scheduled independently of one another. In many instances there will be either a preferred sequence or a mandatory sequence in which certain of the work packages should be performed. When a preferred sequence is not followed unnecessary work will result. For example, suppose that the crane available at the erection site has the capacity to lift the main engine, whereas the one at the outfitting berth does not. The main engine can be lifted aboard as an assembled unit prior to launching. After launching it will be necessary to partially disassemble the main engine, lift the components separately, and reassemble the main engine on board. A mandatory sequence results from the fact that it is physically impossible to perform certain activities prior to others. For example, the electrical cable in a compartment cannot be installed before the compartment has been built. Another factor which precludes performing several work packages in parallel is limited work space. Interference results when too many workers from either the same or different trades are assigned to a confined workspace. Also certain

Certain costs will be incurred when the size of the workforce is either increased or decreased. Increasing the size of the work force can involve the following activities: (1) recruiting; (2) interviewing; (3) testing; (4) performing medical exams; (5) placing; and (6) training. The following often result when the size of the workforce is decreased: (1) exit interviews;(2) separation payments; (3) increased unemployement insurance premiums; and (4) a bad image in the local labor market. Hancock (1971 p. 7-113) stated that the cost for "the leaving of one person and tne hiring of a new one are from $600 to $2,000". These costs do not account for the hyper inflation which has transpired since 1971. If an adjustment for this is made then the current dollar equivalent of these costs would be approximately $1,050 to $3,500.

The typical shipyard has several ships in varying stages of completion at any given time. These ships each compete for a share of the shipyard's manpower and facilities. This competition takes place during each and every period in the planning horizon. Management's task is to determine how the size of each trade's workforce should be changed from period to period so as to minimize the sum of the following: (a) lateness penalty cost; (b) cost of changing the size of the workforce; (c) labor cost; and (d) materials cost. This type of problem is referred to as the multi-resource/multi-project planning problem.

The multi-project/multi-resource planning problem is a very real one in shipyards. This was evidenced by a study in which manufacturing executives in the major U. S. shipyards were asked to rank the causes of delays and cost overruns in shipbuilding (Terry, Green, and Magnuson, 1979).

The most important finding of this survey was that 62.5 percent of the shipyards engaged in Naval construction ranked the unavailability of skilled labor as the most important cause of delays and cost overruns; 37.5 percent of the shipyards ranked improper sequence of assigned labor as the most important cause.

It is obvious from the above that the multi-resource/multi-project (mrmp) planning problems which shipyards must face are extremely complex. Furthermore, the cost of making wrong decisions can be extremely high. This would seem to suggest that shipyards should be using the mrmp planning models. In fact the first such model was described in a paper entitled "Multi-Ship, Multi-Shop, Workload Smoothing Program" (Levy, Thompson, and Wiest, 1963). However, a survey (Terry, Green and Magnuson, 1979) to determine the types of planning tools being used by shipbuilders revealed that not one out of a sample of 21 U. S. shipbuilders were using any type of mrmp planning model (Levy, Thompson, and Wiest, 1963; Lambourne, 1963; Wiest, 1967; Pritsker, Watters, and Wolfe, 1969; Dar-El, Behmoaram, and Tur, 1978). Furthermore, none were using any of the multi-resource/single project models that had been developed. Davis (1973) reviewed the state-of-the-art for such models up through mid-1972. In this paper Davis referred to 138 papers which he deemed to be relevant to the problem of project scheduling under resource constraints. Since this review the following papers have appeared in the open literature: Davis and Patterson, 1973; Dar-El and Tur, 1977; Dar-El and Tur, 1978; Dar-El, Behmoaram, and Tur, 1978; Horroelen, 1973; Patterson, 1973; and Patterson and Huber, 1974. The survey described by Terry, Green, and Magnuson also revealed only half of the shipyards were using PERT or CPM.

None were using the probabilistic features of PERT or the time-cost features of CPM.

The irony of this situation compels the question: why are shipyards not using project planning tools which *prima facie* evidence suggests that they desperately need? The factors responsible for this unexpected result are explored in the following section.

II. FACTORS RESPONSIBLE FOR LACK OF USE OF MULTI-RESOURCE/MULTI-PROJECT PLANNING MODELS

Several factors were identified which were suspected to be responsible for the failure of U. S. shipbuilders to use multi-resource/multi-project (mrmp) planning models. They are: (1) shipyard executives are not aware of the existence of such models; (2) the models are too complicated for shipyard personnel; (3) the models require data that could not be obtained at a reasonable cost; and (4) the models fail to recognize the fact that decisions concerning enterprise goals and the acquisition of resources are typically made at a higher management level than decisions concerned with the allocation of existing resources.

It is quite likely that many shipyard executives are not aware of the existence of mrmp planning models. These models are not usually covered in introductory operations research/management science courses. Most shipyard executives are not likely to be familiar with the journals in which these models have been described. Furthermore, most and perhaps all of the articles on mrmp planning have not been written in a style which would appeal to and be understood by most shipyard executives.

However, the biggest potential barrier to the use of such models arises from their data requirements. Current mrmp planning models require that the user specify the precedence relationships between the various activities involved in building a ship. The size and scope of a ship's construction would result in a combinational problem too large and too expensive for any single heuristic mrmp planning model to handle (Levy, Thompson, and Wiest, 1963; Lambourne, 1963; Wiest, 1967; and Dar-El, Behmoaram, and Tur; 1978).

Another barrier to implementing such models results from the fact that constructing a ship is an evolutionary process (Frisch, 1976). Under such conditions it is not possible to identify a priori all of the important activities which will be involved in constructing a ship. In some situations it will not be possible to specify, at planning time, which of several mutually exclusive approaches for accomplishing a given job will be optimal. Circumstances can arise which can make it necessary to perform certain activities which were in no way expected at planning time. Conversely activities which were believed to be absolutely necessary at planning time can be found to be unnecessary as the project progresses. These difficulties are compounded by the fact that "missing the date on one part of the construction cycle can cause severe cascade effects on other parts" (Corporate-Tech Planning, Inc., 1978, p. D-9). For example, failure to get the main engine installed prior to launch can necessitate partially disassembling it so that its components can be lifted by the crane at the outfit pier. This creates the necessity for assembling it on the ship where work space is limited (Frisch, 1979). The problem of specifying precedence relationships is further complicated by the interaction between ships as evidenced by the following:

> Since all major shipyards have more than one ship under construction at one time, the planning of successive ships is constrained by the status of ships already under construction. Build methods are influenced by other ship work, whether planned or already started. (Corporate-Tech Planning Inc., 1978, p. D-3)

This situation clearly suggests that the precedence relationships tend to

evolve over time as work on the various ships in the yard progresses. This indicates that frequent reruns of the mrmp planning model will be necessary which will magnify the difficulty of an already difficult problem.

Nevertheless it is clear that shipyards need a more effective method for coping with the mrmp planning problem. Evidence to support this claim is provided by the following:

> "Introduction of new or improved management procedures, particularly those which improve ship construction scheduling and thus minimize the present queueing problems that occur when certain shipyard occupations are used intensely for sometime, only to stand idle later. The lessening of insecurity about this layoff/rehire pattern could attract more workers", (Mark Battle Associates, Inc., 1974, p. 8).

This need is particularly great in the outfitting area as noted by Millen (1978, p. 8)

> "Few shipyards can claim to have an effective production planning organization for the steelworking operation which itself is responsible for at least half of the work content of each vessel. Still fewer shipyards achieve any effective planning and coordination of the outfitting departments each of which, because of its relatively smaller contribution and through concern for overhead costs, is usually encouraged to carry out its planning on an informal basis".

The survey of shipyard executives and engineers (Terry, Green and Magnuson, 1979) revealed that most delays occurred in outfitting. This is not

suprising in view of the informal approach to outfit planning. Frisch (1979) observed:

> "When outfitting problems arise there is hardly ever sufficient time to acquire additional resources. The problems typically have to be solved with the resources at hand".

The need for a more effective method for solving the mrmp planning problem is further emphasized by the fact that a sample of 296 Navy ships built since the early 1950's were finished, on the average, 10.5 months late.[1] This represents a great economic loss to both the shipbuilders and the nation.

The following section describes a theoretical framework which provides the basis for developing models for solving the mrmp planning problems of the size and difficulty faced by shipbuilders.

1. The basis for this sample was ship progress curves maintained by the Naval Sea Systems Command.

III. THEORETICAL FRAMEWORK FOR DECOMPOSING MULTI-RESOURCE/MULTI-PROJECT PROBLEMS INTO SOLVABLE PARTS

As seen in the previous section the multi-resource/multi-project (mrmp) planning problems which shipyards encounter are far too large to be solved by existing mrmp planning models. This section describes a two stage approach to decompose this problem into solvable parts: (1) decompose the total problem into strategic and tactical components; and (2) decompose activity network into sub-networks that can be handled separately.

Decomposition into Strategic and Tactical Components

Anthony (1965) provided a taxonomy which classifies planning decisions into two hierarchical levels: strategic planning and tactical planning. This taxonomy provides the basis for the first stage of decomposing the mrmp planning problem into manageable parts.

Strategic Planning. The purpose of strategic planning is to identify the goals of the enterprise, to evaluate the internal strengths and weaknesses of the enterprise, and to monitor the environment to identify problems/opportunities associated with accomplishing these goals. The information obtained from monitoring the environment and evaluating internal strengths and weaknesses typically give rise to two types of questions: (1) How to solve the problems which the enterprise is likely to face in the future? (2) How to exploit the opportunities which are likely to occur? Answers to these questions enable the organization to identify the resources needed to achieve its objectives.

The resource needs of the organization are then translated into

"broad brush" plans for acquiring the needed resources and disposing of those not required. This plan focuses attention on those resources that are costly and/or have long procurement lead times. This plan should specify what the levels of these major resources should be from period to period. In order to do this it will be necessary to determine how these resources should be deployed. However, detailed information on how the major resources should be deployed is not needed for the purposes of formulating this plan. The appropriate level of detail on the intended utilization of such resources should correspond to that needed to make an intelligent decision regarding whether or not the resources should be acquired.

The results of the strategic planning process creates the environment in which tactical decisions must be made. The goal of strategic planning is to create an environment for tactical planning which is in some sense optimal. However, strategic decisions are made in the face of great uncertainty. As the future unfolds uncertainty is reduced. Therefore, strategic plans need to be updated periodically to reflect the impact of intervening events.

Tactical Planning. Tactical planning is concerned with developing action plans for effectively utilizing available resources to accomplish short range objectives which have been derived from the strategic plan. Another function is to plan for the acquisition and disposal of resources as specified in the strategic plan. If the tactical planner is unable to meet the broad general objectives specified by the strategic plan, then the tactical planner should immediately advise the strategic planners

of this situation. There are certain items of detailed information that are considered in the tactical planning process that are either ignored or dealt with in an aggregate form in the strategic planning process. Examples of this type of information are detailed precedence relationships and intercraft and intracraft interference.

Differences Between Strategic and Tactical Planning. Any type of planning must be based on a sample of what is likely to happen in the future. However, strategic planning and tactical planning differ in terms of the type of forecast required. Strategic planning requires a longer range forecast than tactical planning. Tactical planning requires a more detailed forecast than strategic planning. This suggests that the data base which supports tactical planning must be more detailed and updated more frequently than the one for strategic planning. The difference in data base requirements for strategic and tactical planning suggests that using a monolithic model which simultaneously solves both the strategic planning and the tactical planning problems will increase the size of the problem unnecessarily and largely explain why current algorithms are not being used. Furthermore, it overloads both the strategic and tactical planners with irrelevant information. The strategic planner is given too much detail while the planning horizon would be too long for the tactical planner.

The strategic planner has two degrees of freedom which are not available to the tactical planner: (1) freedom to shift target completion dates; and (2) freedom to vary the levels of the various resources from period to period. Making such decisions at the tactical or operational level is

undesirable due to the enormous potential cost of a wrong decision and the limited purview of the tactical planner. However, information indicating a need to revise the strategic plan will not always surface at the strategic management level. When it surfaces at a lower level it should be immediately transmitted to the strategic level.

The inputs to the strategic planning process occur on a more random and less predictable basis than do inputs to the tactical planning process. This suggests that strategic planning should be done on an exception basis while tactical planning should be done on a periodic basis. The rational for this practice is that the time and cost associated with generating a strategic plan are too great to be squandered unnecessarily. What is needed is a more efficient and cost effective means of doing strategic planning, one which is more responsive to important changes in both "internal" and "external" environments. Less important changes should be handled informally if the cost of revising the strategic plan exceeds the benefits of doing so.

The mrmp planning models reported in the literature attempt to deal with both the strategic and tactical planning problems simultaneously, but these cannot cope with the enormous planning problems faced by shipbuilders. These models also fail to recognize that all of the information used in tactical planning is not necessary for strategic planning.

Decompose Activity Network into Sub-networks which can be Solved Independently. Approximately 5,000 work packages (roughly split 50-50 between hull erection and outfitting) are involved in constructing the typical ship (Corporate-Tech Planning, Inc., 1978) which utilizes about

40 trades for its completion (Mark Battle Associates, Inc., 1974). The average work package requires about three months to complete, but these cannot be performed in an arbitrary sequence; for example, either a mandatory sequence or a preferred sequence may exist. A mandatory sequence exists when it is physically impossible to perform certain activities prior to certain prerequisite activities. For example, the main engine cannot be installed until it has been built and the engine mounts have been fabricated. A preferred sequence occurs when it is more cost effective to perform activities in a certain sequence, but nevertheless possible to perform them in a different sequence. For example, heavy piping may be installed at a lower cost when the blocks are being assembled and work space is less restricted than anytime thereafter. Space limitations can also prevent certain activities from being performed simultaneously. Such activities are said to be incompatible. For example, floor coverers and electricians cannot work effectively in the same small compartment.

An enormously large and complicated activity network would be necessary for describing the numerous precedence and incompatability relationships which exist between the 5,000 or so work packages involved in constructing a ship.

The typical shipyard will have several ships under construction at any one time. An enormously large activity network will be required for each of these ships. The number of work packages necessary for the ships in a given shipyard at any given time could run into tens of thousands. Furthermore, these activities will be competing for the limited number of workers in each trade's workforce.

The tactical shipyard planning problem is concerned with allocating each trade's limited workforce to the various activities competing for their services. Shipyard management would obviously like to make this allocation in the most effective manner. However, formulating a mathematical model of this problem could result in a combinatorial problem of immense proportions.

The problem of determining how to allocate each trade's workforce to the various activities is complicated by the great amount of uncertainty in the construction process. This uncertainty manifests itself in two forms: (1) The activity duration times are influenced by a large number of factors which cannot be controlled due to the somewhat exploratory nature of shipbuilding (Frisch, 1976). This makes it difficult to accurately estimate the durations for the various activities. (2) The set of activities necessary for constructing a ship cannot be accurately foreseen. Factors beyond the control of shipyard management can cause the set of activities to change. Frisch (1976, p. 40) gives the following examples of such activities.

> "a subcontractor may not be able to deliver; new weapon developments must be accommodated; weather in open building areas influences worker efficiency".

Changes in the set of activities necessary to construct a ship can be caused by decisions made by shipyard management. For example, the original plan might call for the main engine to be installed prior to launching. However, if building the main engine is delayed shipyard management might decide to install it after launching.

Random variations in activity duration times can be handled by

the probability features of PERT. However, MacCrimmon and Ryavec (1964) have carefully analyzed the assumptions underlying this method. Their analysis revealed a number of fundamental problems which are summarized below.

1. Beta distribution might be appropriate.
2. When there are several paths from the origin node to the terminal node, then the duration of the project is the maximum of the durations of each path. Typically the paths will share common resources. Consequently, they will not be independent. However, even if they are independent the duration of the project will not be normally distributed since the maximum of the two or more normally distributed variables is not normally distributed (Clark, 1961). Furthermore, even if the distribution of the duration of the project is assumed to be normally distributed the PERT procedure yields biased estimates of both the mean and the variance (Tippett, 1925). Specifically, the PERT procedure underestimates the mean and overestimates the variance of the project duration. Furthermore, the degree of bias increases as the number of paths through the network increases.
3. The PERT formulas for calculating the mean and variance restrict the values of the shape parameters of the Beta distribution to the extent that the coefficient skewness of the probability distribution of activity duration can take only three values (-2.5, 2.5, or 0). Thus the contention that the PERT procedure is sufficiently flexible to represent any probability distribution

of activity duration times is misleading.

As a general rule the probability features of PERT are not being used. This is evidenced by the fact that the National Aeronautics and Space Administration no longer includes the probability of meeting schedules in the output of its NASA-PERT system (Moder and Phillips, 1970). Furthermore, none of the shipyards surveyed in Terry, Green, and Magnuson (1979) reported using the probability features of PERT. The most likely reason for this is that most people have difficulty estimating the optimistic and the pessimistic activity durations.

Changes in the set of activities necessary to construct a ship caused by factors beyond the control of shipyard management can be modeled by simulation languages such as GERT (Pritsker, 1974) and TRANSIM (McMichael Orleans, 1975) which permit one of several mutually exclusive arcs leading from a node to be determined probabilistically. However, such a simulation model could not be used to specify how to allocate each crafts workforce to the various work packages. Changes in the set of activities necessary to construct a ship caused by shipyard management decisions can be modeled by the use of Decision CPM (Crowston, W. O. and G. L. Thompson). This technique utilizes total project cost as the basis for selecting a job method from a set of mutually exclusive job methods. Unfortunately this technique is not able to handle uncertainty which results from either random activity durations or from activities which cannot be foreseen.

On the basis of the above, it would appear that the uncertainty in the ship construction process would make a problem which is already

hopelessly difficult even more difficult. Fortunately, this need not be the case. This uncertainty can actually be used to breakup the activity networks for each ship into a number of subnetworks. The rational for doing this rests on the belief that detailed plans should be based on hard facts, indicating that detailed plans should be developed for only those parts of the activity network for which all necessary activities of a major nature can be clearly foreseen.

The horizon for tactical planning should not extend past the point in the activity network at which the first uncertain activity occurs. For example, suppose there is a question as to whether or not the main engine can be built in time to be installed prior to launch. If the engine were ready prior to launch, it can be installed as a unit. If not ready prior to launch, then the crane capacity at the outfit pier would dictate that it be partially disassembled, lifted aboard piece by piece and reassembled <u>in situ</u> which itself represents an additional activity. Furthermore, workspace will be more limited after launch. Thus, installing the main engine post-launch might necessitate using a vastly different work method than required for a pre-launch installation. In addition freeing up the necessary space for assembling the main engine on board might necessitate drastic changes in the sequence in which certain outfitting activities are performed. Thus, it should be obvious that the occurrence of uncertain events could drastically alter the nature of the remainder of the project. Thus, it does not seem prudent to develop detailed plans beyond these points.

Another method for reducing the size of the tactical planning problem is to "schedule the larger items of work and expect the support effort-like

scaffolding, material transfer, lighting, preparation of welding and cutting machines to follow along" (Corporate-Tech Planning, Inc., 1978, p. C-4).

IV. STRATEGIC SHIPYARD PLANNING

Model Formulation

At the strategic level, shipyard management is concerned with: (1) determining target completion dates for the various ships under construction; and (2) specifying how the workforce levels for each trade should be changed from period to period.

Strategic planning is also concerned with determining the most appropriate: (1) financial structure; (2) manufacturing technology; (3) portfolio of assets; and (4) organization structure. The results of these decisions determine the environment in which the strategic shipyard plan must be formulated. As such they can be regarded as super-strategic decisions. For the purposes of the present discussion it will be assumed that the above types of super-strategic decisions have already been made.

None of the multi-resource/multi-project planning models reported in the open literature simultaneously considers both workforce levels and target completion dates as decision variables. Fendley (1968) assumed that resource levels were fixed and considered target project completion dates as decision variables. A number of authors (Levy, Thompson, and Wiest, 1963; McGee and Markarian, 1963; Lambourne, 1963; Moshman, Johnson and Laresen, 1963; Wiest, 1967; and Patterson, 1973) have developed multi-resource/multi-project planning models based on the assumption that due dates for the various projects are fixed. Dar-El and Tur (1978) developed a model which determines resource levels for a single project so as to minimize the "weighted

deviation squares between future resource loads and currently assigned levels". In this model they assumed that the resources required to perform each of the activities was fixed. Penalties for splitting activities and for not scheduling critical activities can be added to the weighted deviation squares. These penalty charges can be varied so as to generate a set of solutions corresponding to different project durations. Bit level storage was used to generate the set of feasible activity combinations for each day. In FORTRAN the unit of storage is a computer word consisting of 32 bits for an IBM 360. Thus, the use of bit level storage makes it possible to reduce storage requirements by a factor of 32 for an IBM 360. It will also result in a substantial reduction in computer effort since logic operations require less time at the bit level than at word level. Nevertheless these computational refinements will not be sufficient to allow their algorithm to be generalized to handle multi-resource/multi-project problems in which both target completion dates and resource levels are decision variables.

Clearly, the state-of-the-art as reported in the literature indicate that a new model be developed for solving mrmp planning problems. A prerequisite for developing a model for the strategic shipyard planning problem is a clear understanding of how workforce levels and project completion dates impact cost.

Note that the total cost of the portfolio of ships under construction is not influenced by the completion date of a given ship up to the time at which the completion date exceeds the due date. After the due date, cost increases due to the lateness penalty charges for the ship which is

late. However, being late on one project can create a series of events which can cause the cost of other projects to increase. For example, being late on one ship might delay the start of a number of other ships. This could increase costs in several ways. Lateness penalty charges could be incurred on subsequent ships which would not have been incurred otherwise. However, it might be possible to reduce these lateness penalty charges by temporarily increasing the size of the workforce, but this will cause certain additional costs to be incurred. When the workforce is expanded it will be necessary to: (1) recruit; (2) interview; (3) test; (4) examine; (5) place; and (6) train the new employees. Reducing the size of the workforce can involve: (1) exit interviews; (2) separation payments; (3) increased premiums for employment insurance; and (4) a bad image in the local labor market. The manner in which the size of the workforce influences total cost for a portfolio when all other decision variables are held constant, is illustrated by Figure 1 .

This figure shows that total costs increase more sharply as the size of the workforce is decreased than for the case in which it is increased. However, this will not always be the case.

Wage rates for each of the trades and unit costs for the various materials will tend to increase abruptly at discrete points in time due to inflation. This is illustrated by the graph in Figure 2 which shows how the wage rate for a given trade changes with the passage of time.

Both the points in time at which such increases occur and their amounts can often be determined from the multi-year union contracts. A similar type step function will typically exist for each of the trades and each of the raw materials. For many raw materials price increases

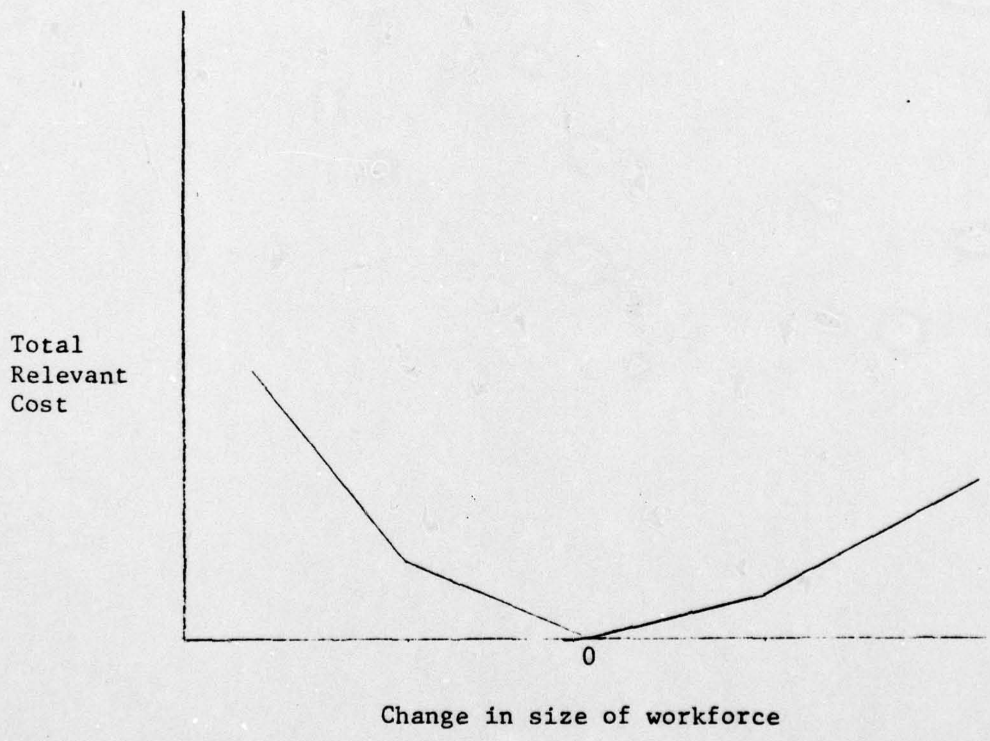


FIGURE 1. Influence of change in workforce size to total relevant cost.

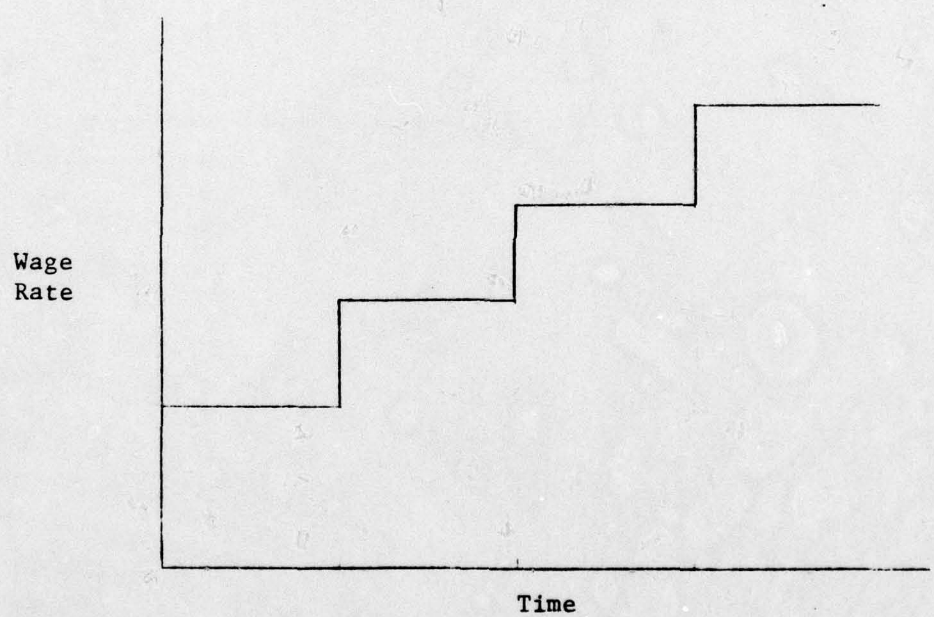


FIGURE 2. Wage rate increase for a given craft at specific points in time.

tend to be announced at specified times during the year. Forecasting the size of such increases will require an analysis of the factors which influence both the supply and demand for the material in question. Inflation in wage rates for the various trades and unit cost of raw materials cause total cost to increase as the duration of a particular ship construction project increases. This is depicted by Figure 3.

The time required to complete a given ship will depend on the number of workers for each trade assigned to work on it during each time period. This is illustrated by Figure 4 which shows two hypothetical percentage completion curves for constructing a given ship.

The most obvious way in which completion dates influence cost is through late delivery penalty charges. The penalty cost for late delivery consists of: (1) penalty payments for late delivery explicitly specified in the contract; and (2) opportunity costs of the shipyard facilities tied up by the late delivery. In theory, bonuses for early delivery are possible. However, they are rarely encountered in practice and will not be considered as part of the model. Figure 5 illustrates how the total cost of a portfolio of projects behaves as the completion date of a single ship is varied given that all other variables which influence total costs are held constant.

The strategic shipyard planning problem is to determine the target completion dates and workforce levels for each trade during each period in the planning horizon such that total relevant cost will be minimized. The following notation will be used in formulating a mathematical model of this problem:

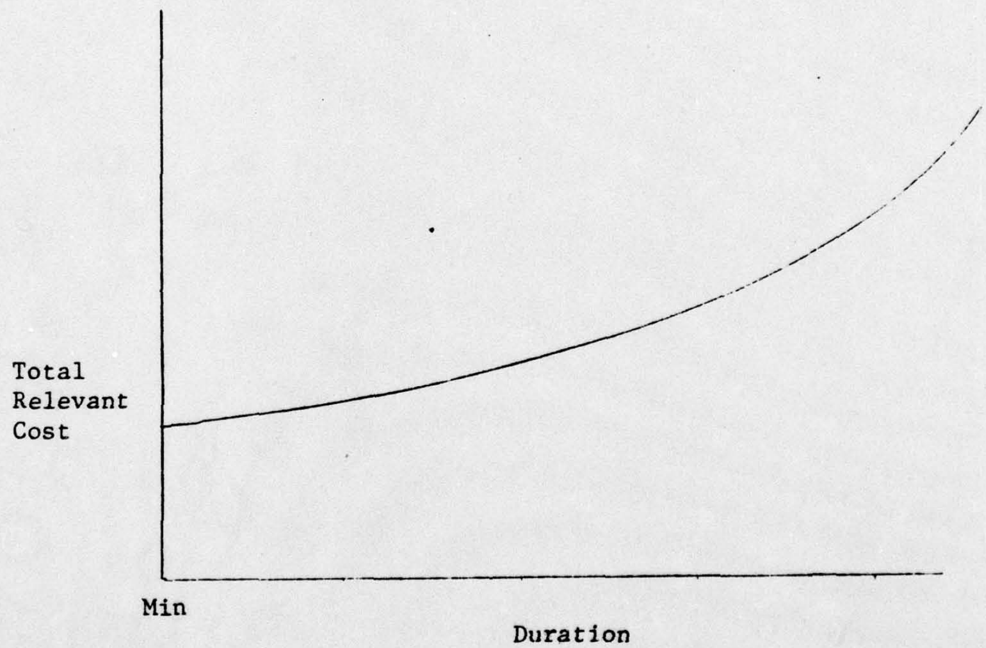


FIGURE 3. Inflation in wage rates and cost of raw materials increases total cost of a portfolio of ship construction projects as the duration of a project increases.

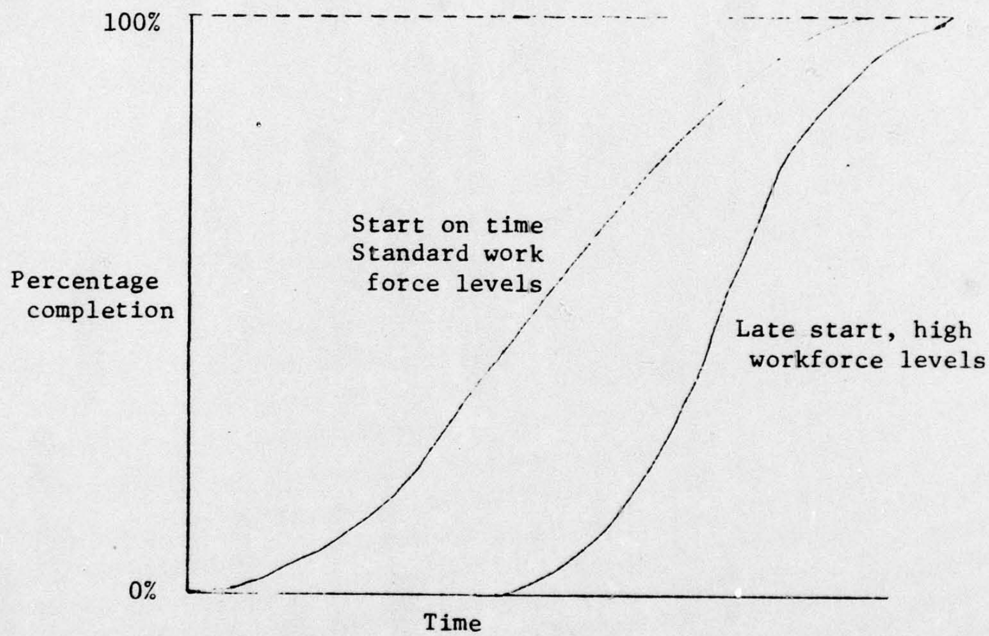


FIGURE 4 . Impact of start date and labor application rates on completion time.

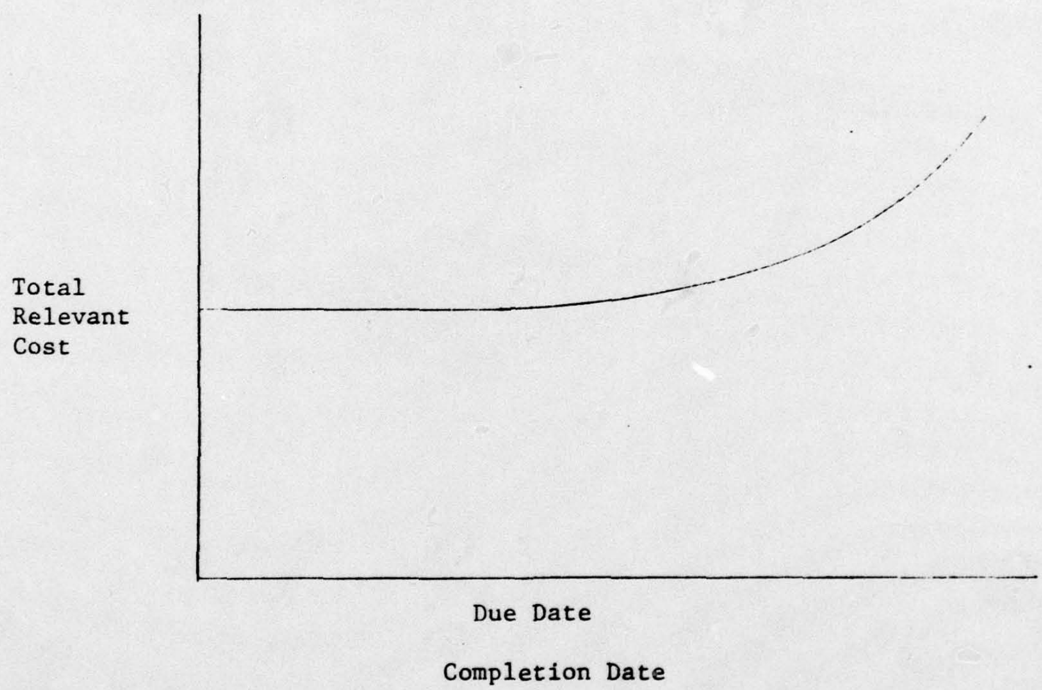


FIGURE 5. Impact of completion date of a given ship on total cost of a portfolio ship construction project given that all other decision variables which influence total cost are held constant.

i = index for trades

I = index set of trades, i.e., $I = \{i\}$

j = index for ships

J = index set of ships, i.e., $J = \{j\}$

labor

- x_{ijt} = labor hours of trade i assigned to ship j during period t
- y_{it} = labor hours of trade i available during period t
- w_{ij} = total number of estimated labor hours of trade i required on ship j
- c^{ℓ}_{it} = unit cost per labor hour of trade i for period t

material

- k_{ij} = the amount of material required per labor hour of trade i assigned to ship j
- c^{m}_{it} = unit cost of material associated with craft i for period t

hiring

- h_{it} = labor hours of craft i hired during time period t
- u^{h}_{i} = upper limit on the number of labor hours of craft i hired during any period
- c^{h}_{i} = cost of hiring a labor hour of craft i

laying off

- ℓ_{it} = labor hours of trade i layed off during time period t
- u^{ℓ}_{i} = upper limit on the number of labor hours of trade i layed off in any period
- c^{ℓ}_{i} = cost of laying off a labor hour of trade i

S_j = start date for ship j

$$\begin{array}{l}\text{timeliness/} \\ \text{lateness}\end{array}\left\{\begin{array}{l} D_j = \text{due date for ship } j \\[1em] T_j = \text{delivery date for ship } j \\[1em] L_{jt} = \text{cost of lateness for ship } j \text{ in period } t \end{array}\right.$$

P = number of periods in the planning horizon

$$z_{jt} = \begin{cases} 0 \text{ if construction on ship } j \text{ is not permitted during period } t \\ 1 \text{ if construction on ship } j \text{ is permitted during period } t \end{cases}$$

In formulating this model it will be assumed that:

(1) all hiring and laying off is done at the beginning of each time period;

(2) shipyard facilities are adequate and that lack of such facilities will not constitute a major source of delay;

(3) both intertrade and intratrade interference are negligible;

(4) overtime is not permitted;

(5) strict precedence relationships, which specify that activity B cannot be started until activity A has been completed, are not necessary in view of the resulting long time periods used in strategic planning.

The last three assumptions are made to reduce the size and complexity of the problem so that it will be solvable. However, these factors will be explicitly considered in the tactical shipyard planning model.

Total relevant costs consists of the sum of: (1) cost of late deliveries; (2) labor costs; (3) materials costs; (4) hiring costs; and

(5) layoff costs.

The cost of late deliveries is given by

$$\sum_{j \varepsilon J} \sum_{t=D_{j+1}}^{P} L_{jt} \; z_{jt} \qquad (1)$$

If ship j is not completed until period D_j+n then penalty costs will be incurred in periods D_j+1 to D_j+n. This results from the fact that the binary decision variable z_{jt} was defined to be equal to one for the case in which construction on ship j is permitted during period t.

Labor costs are given by the following expression:

$$\text{Labor costs} = \sum_{t=1}^{P} \sum_{i \varepsilon I} c_{it}^{\ell} \; y_{it} \qquad (2)$$

Materials costs are given by

$$\text{Materials costs} = \sum_{i \varepsilon I} \sum_{j \varepsilon J} \sum_{t=s_j}^{T_j} c_{it}^{m} \; k_{ij} \; x_{ijt} \qquad (3)$$

This equation is based on the assumption that trade i consumes materials at the rate of k_{ij} units of material per labor hour working on ship j.

The cost of hiring additional workers is given by

$$\text{Hiring costs} = \sum_{t=1}^{P} c_i^h \; h_{it} \tag{4}$$

while the cost of laying off workers is given by

$$\text{Layoff costs} = \sum_{t=1}^{P} c_i^{\ell} \ell_{it} \tag{5}$$

Thus the objective is to minimize the sum of the quantities in equations 1 through 5 subject to a number of constraints which must be satisfied in order for a solution to the problem to be valid.

$$\sum_{t=1}^{P} x_{ijt} = w_{ij} \qquad \text{for all } i, j \tag{6}$$

This constraint states that the total number of hours of trade i assigned ship j during the periods in the planning horizon must be equal to the total number of hours of trade i needed to construct ship j.

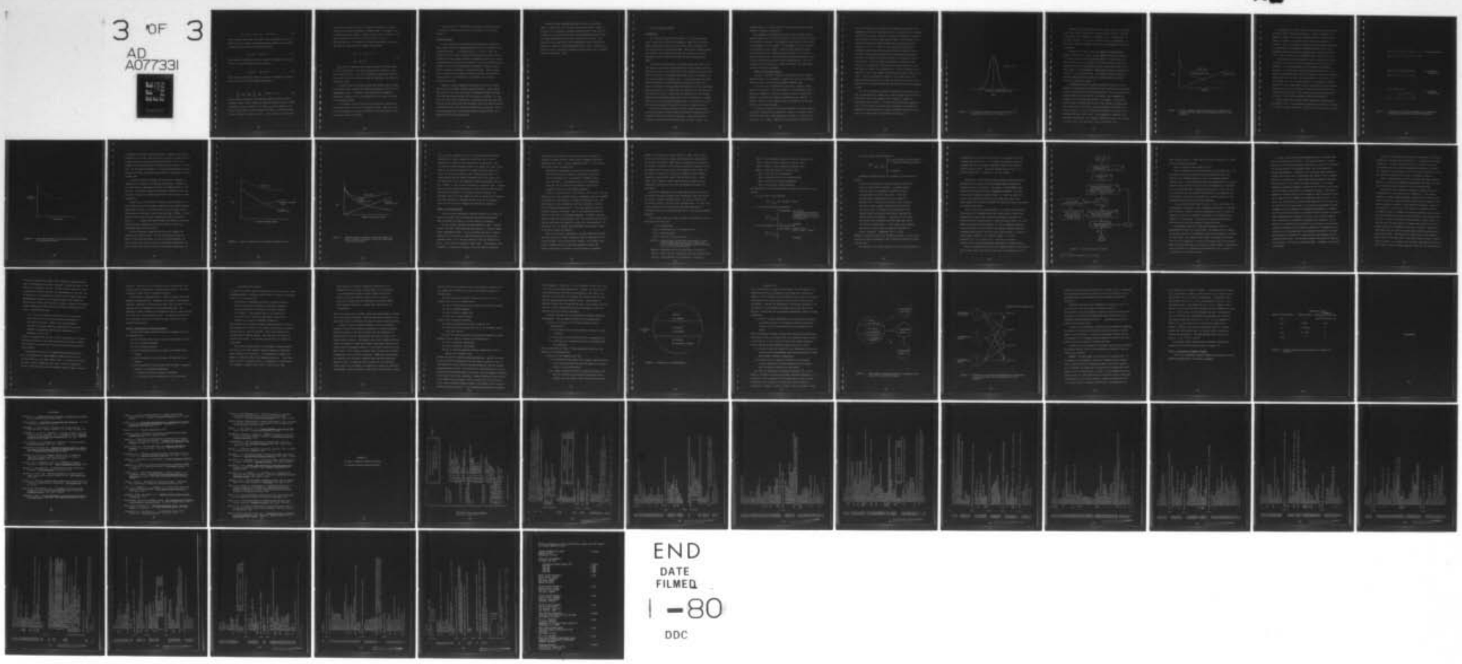
$$\sum_{j \varepsilon J} x_{ijt} \; z_{jt} \leq y_{it} \qquad \text{for all } i, t \tag{7}$$

This constraint states that the total number of hours of trade i assigned to each of the J ships under construction during time period t must not exceed the number of hours available in the trade i workforce.

AD-A077 331 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 13/10
ANALYSIS OF THE COST OF VARIABLE WORKLOADS ON SHIPBUILDING.(U)
NOV 79 A H MAGNUSON , R W TERRY N00014-78-C-0411
UNCLASSIFIED VPI-AERO-103 NL

3 OF 3

AD
A077331



END
DATE
FILMED
1 -80
DDC

$$y_{it} = y_{it-1} + h_{it} - \ell_{it} \quad \text{for all i, t} \tag{8}$$

This constraint states that the size of craft i workforce at time t is equal to its size during the preceeding period adjusted for the number of workers hired and laid off during that period.

$$h_{it} \leq u_i^h \quad \text{for all i, t} \tag{9}$$

This constraint states that there is a limit to the number of workers in trade i that can be hired during time period t.

$$\ell_{it} \leq u_i^\ell \quad \text{for all i, t} \tag{10}$$

This constraint states that there is a limit to the number of workers in trade i that can be laidoff during time period t.

$$\sum_{t=1}^{T} x_{ijt} \leq r_{igj} \sum_{t=1}^{T} x_{gjt} \quad \text{for T=1, 2.....p} \tag{11}$$

This constraint states that the cumulative number of hours of trade i assigned to ship j cannot exceed the cumulative number of hours of trade g assigned to ship j multiplied by a factor r_{igj} which represents the ratio of total number of hours required for trade i to the total number of hours required for trade g on ship j. This constraint is needed for

only those situations in which the cumulative progress of one trade restricts the cumulative progress of another trade. For example, such a constraint would be needed to reflect the fact that the number of steel plates welded into place can't exceed the number of plates that have been cut. In addition to the above constraints the decision variables are restricted to the ranges defined below.

$$x_{ijt} \geq 0, \; y_{it} \geq 0$$
$$z_{jt} = (0 \text{ or } 1) \tag{12}$$

The model as formulated above limits attention to a finite number of future time periods. The typical shipyard will continue to exist well beyond this time. Thus, it is necessary to ensure that the sizes of the work forces for the various trades be consistent with operations beyond that point.

If periods beyond the planning horizon are ignored, then the model as formulated could recommend dismissing all employees at the end of the recommended horizon. Fortunately, this problem can be handled by specifying a minimum size for the workforce for each craft at the end of the planning horizon.

It is possible that not all ships in the shipyards order backlog can be completed by the end of the planning horizon. When this arises it will be necessary to specify the amounts of work which must be done on each ship during the horizon.

The above model is a mixed integer quadratic programming problem. A procedure for solving this problem is described in the following section.

Solution Strategy

To date there have been no algorithms developed for solving the mixed integer quadratic programming problem that was formulated in the preceeding section. A strategy which can be used to solve this problem consists of using the projection technique (Geoffrion, 1970) to transform the mixed integer quadratic programming problem into a linear programming problem which will be referred to as the inner minimization problem. This will be accomplished by temporarily fixing the binary decision variables according to a specified pattern. These patterns will be determined in a sequential fashion according to the method of steepest decent. This process will be referred to as the outer minimization problem.

Commercial linear programming codes appear to be able to handle real world size strategic shipyard planning problems. Lasdon (1978) has noted that such codes are capable of handling problems with 8,000 to 16,000 rows provided sufficient core storage is available. He also notes that even larger problems with a generalized upper bounding structure can be solved and notes that Hirschfeld (1972) has reported solving a 50,000 row problem with generalized upper bounding structure. This is most encouraging since the strategic shipyard planning problem has a generalized upper bounding structure.

The above linear programming problem will have to be solved a number of times since it is the inner maximization problem. However, the nature of the strategic shipyard planning problem is such that composition of the optimal basis for the linear programming problem should not change appreciably from one search iteration to the next. This situation can be exploited to reduce computation time by utilizing the capacity of commerical linear programming codes to save a previous optimal basis so as to provide an advanced starting solution for a subsequent problem (Orchard-Hays, 1974).

V. TACTICAL SHIPYARD PLANNING

Introduction

The strategic shipyard plan specifies: (1) target completion dates to the various ships on the shipyard's order book or currently under construction; and (2) the size of each trade's workforce for each period during the planning horizon. These target completion dates and workforce levels represent respectively the goals for tactical management and the resources which they can use in pursuing these goals.

The tactical planners task is to develop plans which specify for each period in the tactical planning horizon how each trade's workforce should be allocated to the various activities necessary for constructing each of the ships. In developing these plans it will be necessary for the tactical planner to recognize that: (1) both intertrade and intra-trade interference can cause substantial productivity losses; (2) failure to consider strict precedence relationships can cause unnecessary delays and costs to be incurred; and (3) overtime can be used when it is cost effective to do so. Recall that the formulation of the strategic shipyard planning problem assumed that it was not necessary to consider these factors at the strategic planning level. This was done to reduce the size and complexity of the problem so that it could be solved.

The tactical planning process is further complicated by random variation in activity duration times and uncertainty regarding sets of activities which will actually be necessary. These factors make it necessary to revise tactical shipyard plans from time to time. The

combined effect of the above factors imply that the tactical planning problem is enormously complicated.

The complexity and importance of the tactical shipyard planning problem suggests that it would be desirable to have an efficient method for solving such problems. The purpose of this section is to describe the development of such a method. The development of such a procedure is accomplished in four phases. The first phase specifies a model which describes how the variables under the control of the tactical planner influence cost. The second phase analyzes and evaluates existing multi-resource/multi-project (mrmp) planning models. The third phase develops a procedure for solving the problem. The fourth phase programs the solution procedure.

Phase 1: Model Specification

In order to formulate a model for solving the tactical shipyard planning problem it is necessary to identify how each of the variables under the control of the tactical planner influences cost.

If a project is not completed on time, then a lateness penalty cost will be incurred. This cost consists of the opportunity cost of having the shipyard's productive facilities tied up and additional payments of late delivery explicitly specified by the contract. In addition, failure to meet delivery dates can jeopardize the shipyard's ability to get future business.

The tactical planner can influence the amount of lateness penalty cost which a shipyard incurs through the choice of the times at which activities which have a high probability of being on a critical path are started. For example, suppose that each activity on the critical

path for a given ship is started at its appropriate time based on the assumption that each of the activities will be completed in the expected time for that activity. However, the actual time required to complete each activity will tend to vary about its mean. This variation in the actual critical path activity duration time will cause the project duration to vary. As a result of the central limit theorem the probability density function for project duration times will tend to be normally distributed with mean and variance respectively equal to the sum of the means and variances for each of the activities on the critical path. Since the normal distribution is symmetrical this implies that starting each activity on the critical path at its late start date will result in a probability of .5 that the project will be completed on time (this assumes that other "near critical" paths do not exist). This is illustrated in Figure 6 which shows that if the expected completion date for a project is equal to its due date, then there will be a 50 percent chance that the project will not be completed on time.

The tactical planner can reduce the odds that the project will be late by starting some or perhaps all of the activities on the critical path earlier than their respective start times (for example, by increasing resource levels). This will cause the expected completion date to be less than the due date which corresponds to shifting the probability density function for project completion times to the left. This will in turn reduce the probability of being late.

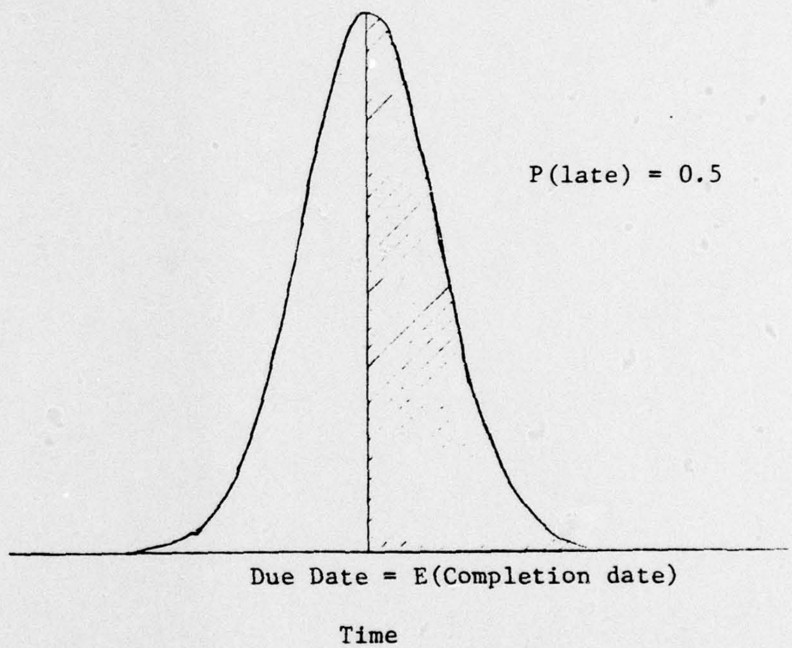


FIGURE 6. If expected completion date equals due date, then probability of being late is equal to 0.5.

Starting the critical path activities earlier than their scheduled start times can be visualized as insurance against lateness. The cost of resources can be regarded as the premium on the insurance policies for the activities. The tactical planner's task is to determine: (1) how much to spend on insurance; and (2) the best portfolio of policies to purchase.

Overtime can be used to reduce the amount of lateness penalty charges incurred when a project is not completed on time, but the use of overtime involves overtime premium payments. If there are two or more activities on which overtime can be used to reduce the amount of lateness and these activities both use one or more trades which are in short supply, then the problem of determining the optimal allocation of overtime, to the activities arise. The tradeoff between lateness and overtime, assuming that all other cost influencing factors are held constant is depicted by Figure 7.

In shipbuilding there are certain situations in which it is not possible to simultaneously perform two or more activities as efficiently as the activities could be performed separately. This can arise when two trades interfere with the work of one another. This phenomenon is referred to as intertrade interference. For example, if electrical cables, pipes, and ventilation ducts all pass through a confined space then electricians, pipefitters, and vent installers could impede each other's progress. It is also possible for members of the same trade to interfere with each other's work. This phenomenon is referred to as intratrade interference. For example, assigning too many floor coverers to a given area could cause each to get in the other's way.

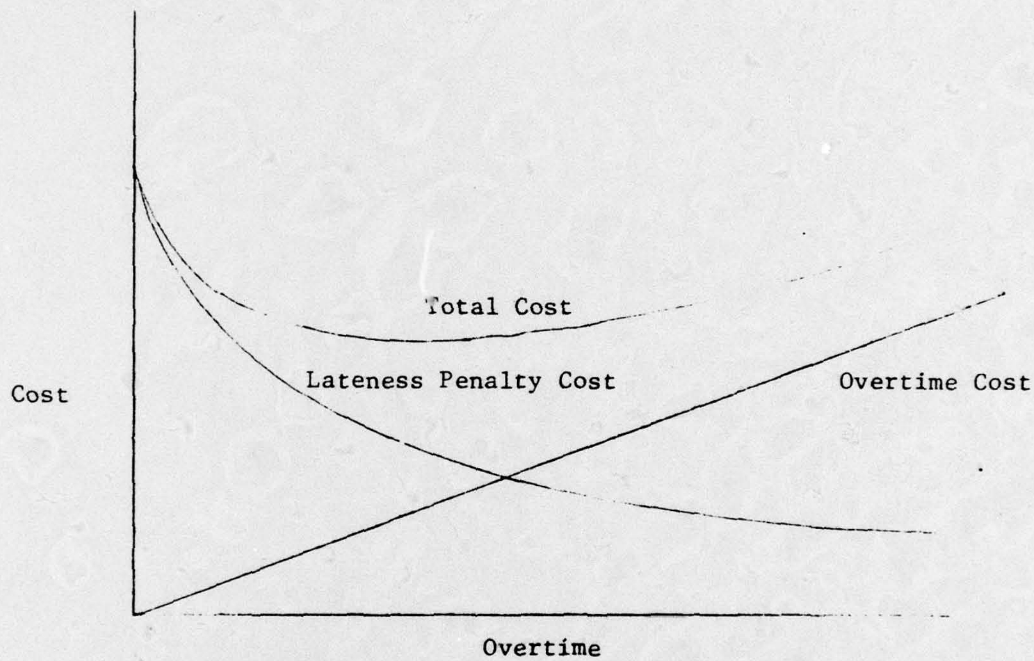


FIGURE 7. Tradeoff between lateness penalty cost and overtime cost assuming that all other cost influencing factors are held constant.

The duration of a project can be reduced by judiciously utilizing intertrade and/or intratrade interference. This is illustrated by Figure 8. However, if the use of intertrade and/or intratrade interference is carried to the extreme, then the project duration will increase. This is illustrated by Figure 9 where the minimum represents the point where the incremental time reduction which results from performing certain activities in parallel and/or using more workers on a job is exactly offset by the interference which results from such.

Some activities can be scheduled to start at anytime while others cannot be started until a set of prerequisite activities have been satisfied. These prerequisites can be classified as mandatory or preferred. A given activity cannot be accomplished until all of its mandatory prerequisites have been met. Failure to satisfy all preferred prerequisites will not block the accomplishment of the activity, but will increase the cost of accomplishing it. For example, it might be desirable to paint compartments prior to installing floor coverings and fixtures since this will eliminate the need for covering floors and fixtures with drop cloths. Thus, another option for reducing project lateness is to selectively disregard preferred prerequisites.

Random variations in delivery date leadtimes can cause material shortages to arise. Such shortages can delay the start and/or completion of certain of certain activities. When an activity on the critical path

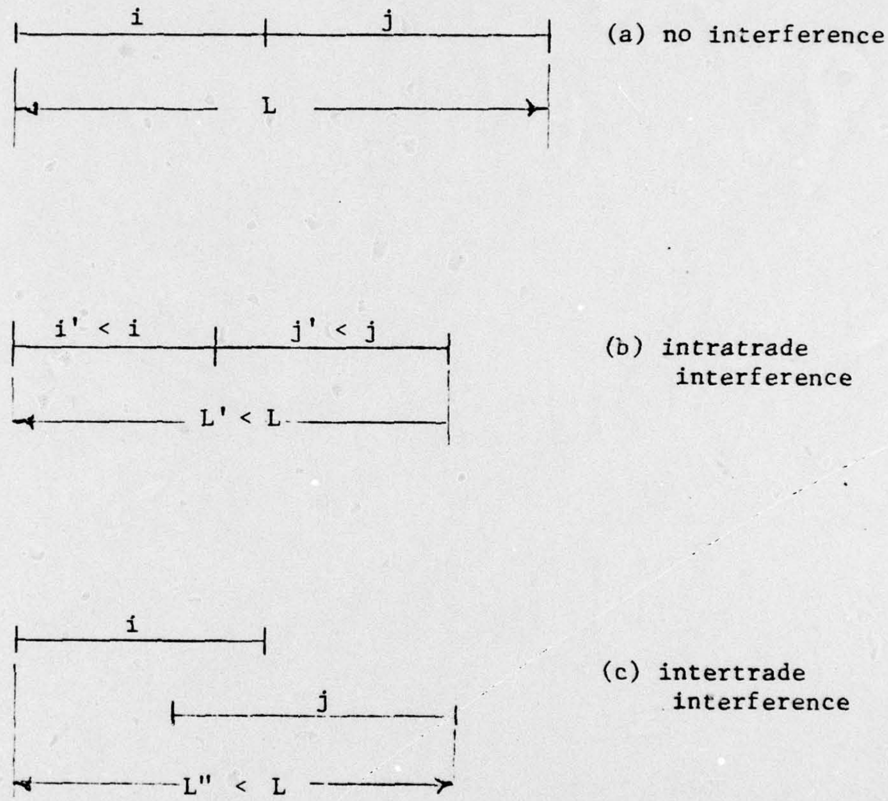


FIGURE 8. Illustration of how project duration can be reduced by utilizing intertrade and intratrade interference.

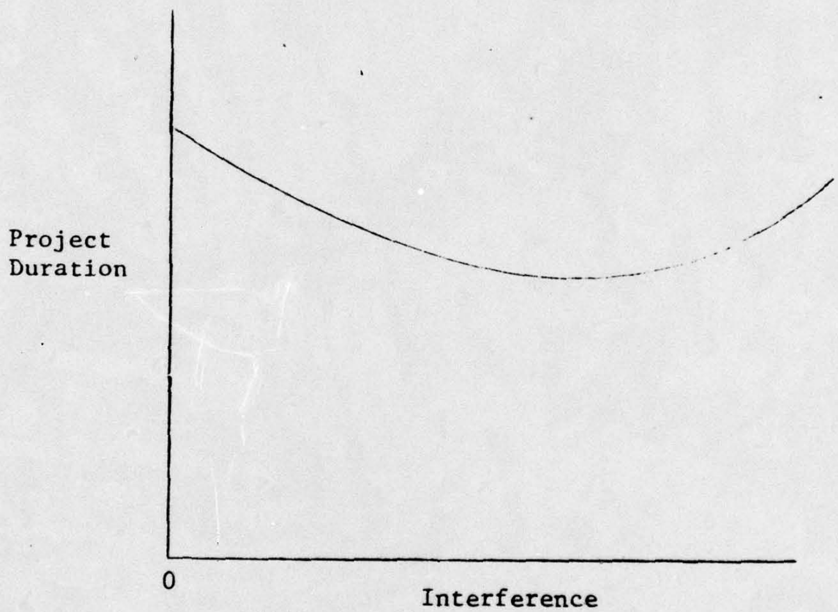


FIGURE 9. Relationship between the project duration and the degree of interference allowed.

is delayed, then project lateness can result. However, this need not necessarily be the case, since there are a variety of actions which can be taken to make up for the time loss caused by the delay. For example, the following methods for reducing project duration: (1) overtime, (2) intertrade interference, (3) intratrade interference, and (4) activity splitting; can be used more extensively than called for in the predelay plan.

The risk of material shortages can be reduced by allowing for longer delivery leadtimes in purchasing raw materials. However, use of longer delivery leadtimes will result in increased inventory carrying cost. The tradeoff between the additional leadtimes for the case in which all other cost influencing factors are held constant is shown in Figure 10.

Another option for reducing the amount of project lateness is to shift workers from activities whose completion can be postponed without causing their project to be completed late to a more urgent activity. This situation is referred to as activity splitting. However, this will typically cause set-up cost and transportation costs to increase. Figure 11 depicts the tradeoff between the number of activities split and project lateness for the case in which all other cost influencing factors are held equal.

The above discussion suggests that the tactical planner can influence the following costs: (1) cost of productivity lost as a result of splitting activities; (2) cost of overtime premiums; (3) cost of productivity lost as a result of intertrade interference; (4) cost of productivity lost as a result of intratrade interference; (5)

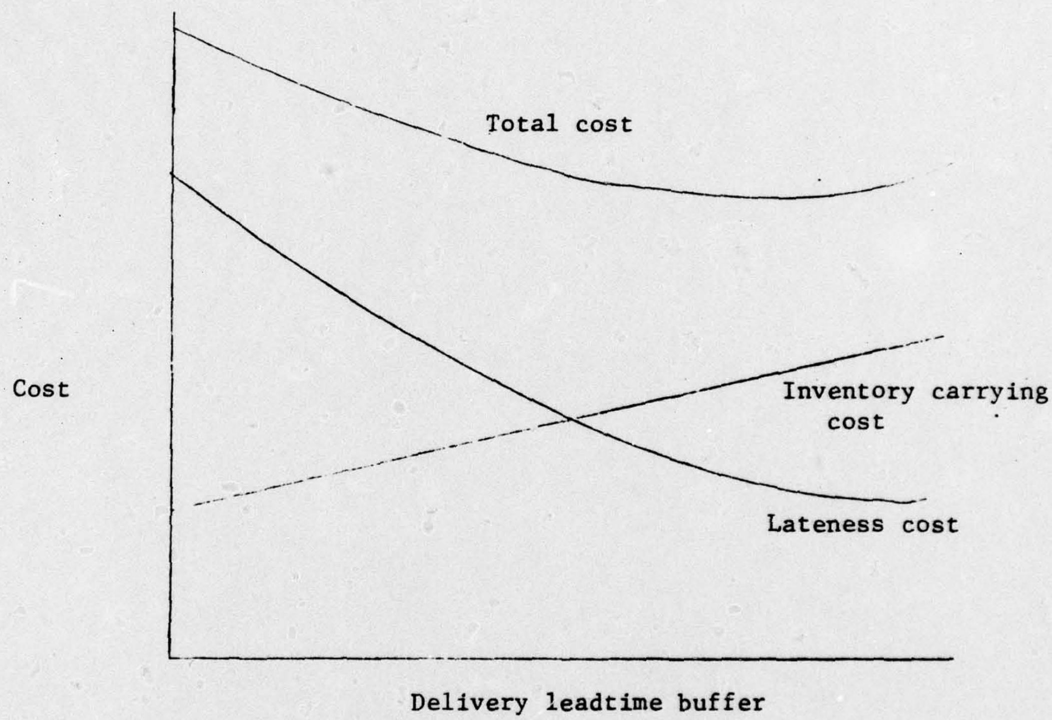


FIGURE 10 . Impact of safety stock for delivery leadtime on cost.

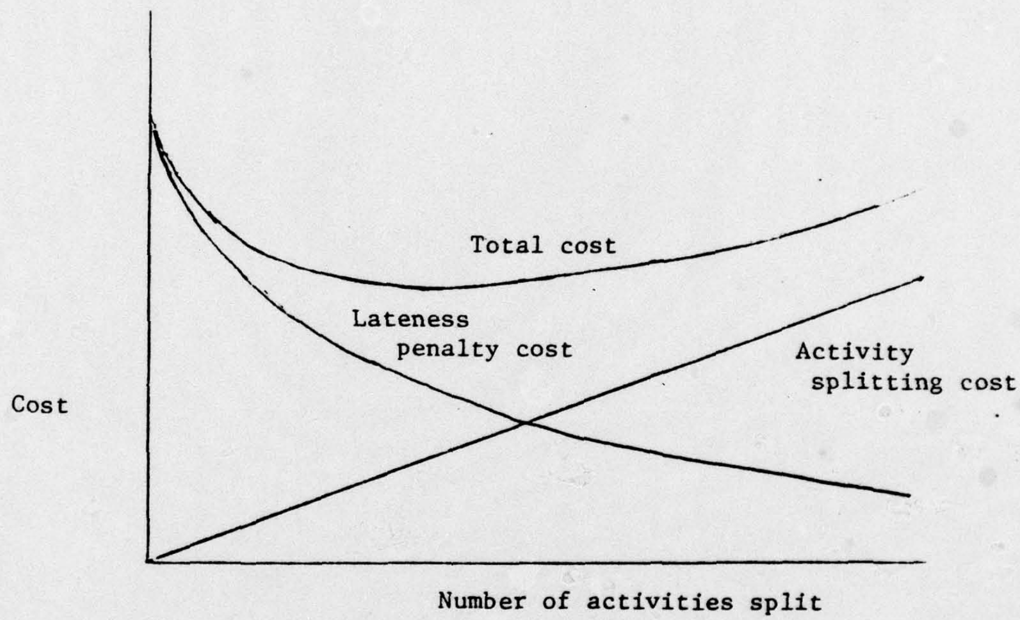


FIGURE 11 . Tradeoff between the number of activities split and project lateness in which all other cost influencing factors are held equal.

cost of project lateness; (6) cost of carrying additional material inventories to protect against late deliveries; and (7) cost of disruption as a result of late deliveries of key materials. Thus the tactical shipyard planning problem is to assign each trade's work-force to the various activities in a manner which will minimize the sum of the above costs subject to the following constraints: (1) resource availabilities cannot be exceeded; and (2) no activity can be started until all of its mandatory precedent requirements have been met. However, an idle resource represents an opportunity loss. Therefore, the cost of idle time associated with tactical shipyard plans should be calculated and reported to the strategic shipyard planner. The strategic planner will then compare the cost of laying off and rehiring of workers necessary to eliminate the idle time with the savings in labor cost and revise the strategic shipyard plan if necessary.

Phase 2: Literature Review

The next step in developing a solution procedure is to review the solution strategies used in solving existing mrmp planning models. These procedures are found to be either analytic or heuristic.

Only one analytic approach has been published to date. Pritsker, Watters, and Wolfe (1969) formulated the problem as a zero-one integer linear programming problem. Zero-one variables are used to indicate whether or not an activity is completed during each period in the planning horizon. If it has been completed, then its successors may start. If not, then its successors cannot start. Unfortunately, such an approach, if applied to problems of the size faced by shipyards,

would result in a problem the size of which would far exceed the capacity of present zero-one integer linear programming algorithms (Wiest and Levy, 1977). In fact, Elmaghraby (1977, p. 217) reported that Lenstra (1976) has shown that:

> The problem of scheduling activities on multiple resources when the activities are subject to precedence constraints and the availability of the resources is limited is known to be "NP hard".... This implies that, in all probability, there shall be no "efficient" algorithm for solving this problem (in the sense of achieving optimality).

A number of authors (Fendley, 1968; Gonguet, 1969; Pascoe, 1964; and Patterson, 1973) have reported simulation experiments that were designed to evaluate the effectiveness of a number of scheduling rules. The effectiveness of these scheduling rules were evaluated in terms of of the following characteristics: (1) on time completion; and (2) efficient resource utilization. None of the scheduling rules were found to be best for all performance measures. In general, due date oriented scheduling rules performed better than resource oriented rules when the performance was measured in terms of on time completion. The reverse was true, in general, when performance was measured in terms of efficient resource utilization.

None of the heuristic approaches to the mrmp scheduling problems with the exception of a model developed by Dar-El, Behmoaram, and Tur (1978) utilized a cost based objective function. The heuristic used in Levy, Thompson and Wiest (1963) was designed to reduce peak resource requirements and smooth out period-to-period assignments

subject to a constraint on project duration. SPAR-1 (Wiest, 1967) utilizes a heuristic which places primary emphasis on completing the job as early as possible. RAMPS which was developed for proprietary use utilizes a heuristic which involves minimizing a weighted function of variables such as total slack, idle resources, project delay cost, and number of successors to a given job (Lambourne, 1963; Moshman, Johnson and Laresen, 1963; Wiest, 1963; and Wiest, 1969). Jenett (1970) lists a number of other network analysis programs which are commercially available but for which the scheduling heuristic are kept secret.

The Dar-El, Behmoaram, and Tur (DBT) model was found to provide an excellent conceptual foundation for developing a model for solving the tactical shipyard planning problem. The objective function of this model is equal to the sum of the following terms: (1) total cost of idle resources; (2) total activity splitting penalties; (3) incremental total cost of overtime work; and (4) total project lateness penalties.

The following notation is used to specify the formulas for calculating each of the above cost:

CD = calendar date

CF(i) = expediting factor for resource type i

CL(j) = lateness penalty

CS(i) = unit cost for resource type i

CSLK(j,k) = critical slack for activity k on project j (a user fixed parameter which can be used to specify the priority associated with starting critical activities prior to their late start date)

DUR(j,k) = remaining duration of the activity k on project j

HRA(i) = higher resource availability level for resource type i

LF(j,k) = late finish date of the activity k on project j

LRA(i) = lower resource availability level for resource type i

RA(i) = number of units available of resource type i

RR(i) = number of units required by resource type i

SPEN(i) = splitting penalty for resource type i

TCIR = total cost for idle resources

TCOT = incremental total cost of overtime work

TASP = total activity splitting penalties

TPLP = total project lateness penalties

The formulas for the constituent terms in the objective function are as follows:

(1) total cost of idle resources

$$\text{TCIR} = \sum_{\text{All } i} [\text{RA }(i)-\text{RR}(i)] * \text{CS}(i)$$

(2) total activity splitting penalties

$$\text{TASP} = \sum_{\text{All } i} \begin{cases} \text{SPEN}(i)*\text{RR}(i) & \text{if activity was scheduled in immediately preceeding period, but not completed, and not scheduled on current day} \\ 0 & \text{otherwise} \end{cases}$$

(3) total incremental cost of overtime work

$$\text{TCOT} = \sum_{\text{All } i} \begin{cases} \text{RR}(i)-(\text{HRA}(i)) *\text{CS}(i)*\text{CF}(i) & \text{if } \text{LRL}(i) < \text{RR}(i) < \text{HRA}(i) \\ 0 & \text{otherwise} \end{cases}$$

(4) total project lateness penalties

$$\text{TPLP} = \sum_{\text{All } j} \sum_{\text{All } k} \begin{cases} \left(\text{CD}-\text{LF}(j,k)-\text{DUR}(j,k)-\text{CSLK}(j,k)\right)*\text{LP}(j) \\ \qquad \text{if CD}>\text{LF}(j,k)-\text{DUR}(j,k)-\text{CSLK}(j,k) \\ 0 \quad \text{otherwise} \end{cases}$$

Behmoaram explained the need for a purpose of critical slack as follows:

> "An activity whose start is delayed beyond its late start date will cause project tardiness. A lateness penalty should be paid if an assignable (candidate) activity.... is delayed beyond its late start date.... Thus when lateness penalty applies the project is already in a potential state of being late and since certain resources are scarce, there is great likelihood that some project delay will occur. To increase the effectiveness of the lateness penalty and thereby avoid project tardiness the critical slack is introduced.... the critical slack causes the activity to be considered late CSLK time units before the activity is really late.... The critical slack therefore operates as a safety factor to reduce the likelihood of project tardiness". (Behmoaram, 1976, p. 27-30)

However, he failed to discuss two important questions: (1) How should the value of CSLK be determined?; and (2) What form should the penalty function take?.

The problem is to allocate resources to the various activities in

a manner which will minimize total relevant cost subject to the constraints which specify that: (1) resource availabilities cannot be exceeded; and (2) all precedent requirements must be met before an activity can be started. This model assumes that the level of each resource availability is constant for all time periods.

Dar-El et al. (1978) realized that a heuristic approach would be necessary for solving real world sized mrmp planning problems and developed a heuristic approach. This model is called SCREAM (SCarce REsource Allocation Model) and is programmed in FORTRAN. The basic flow chart for SCREAM is shown in Figure 12. Note that each block in this flow diagram has a number in the upper right hand corner. These numbers will be used to identify the blocks when they are discussed in further detail below.

Block 1 reads in the following data: (1) arrival and due dates of every project; (2) lateness penalty and critical slack (a user fixed parameter which can be used to specify the priority associated with starting critical activities prior to their late start dates); (3) total number of activities in each project; (4) set of immediate followers for each activity; (5) the levels of the various resources required to accomplish each activity; (6) unit cost of each resource; (7) amount of each resource available ; (8) maximum amount of overtime permitted for each resource; (9) overtime cost for each resource; and (10) splitting penalties associated with each resource.

Block 2 calculates the critical path completion date for each project and the early start, early finish, late start, late finish, and total

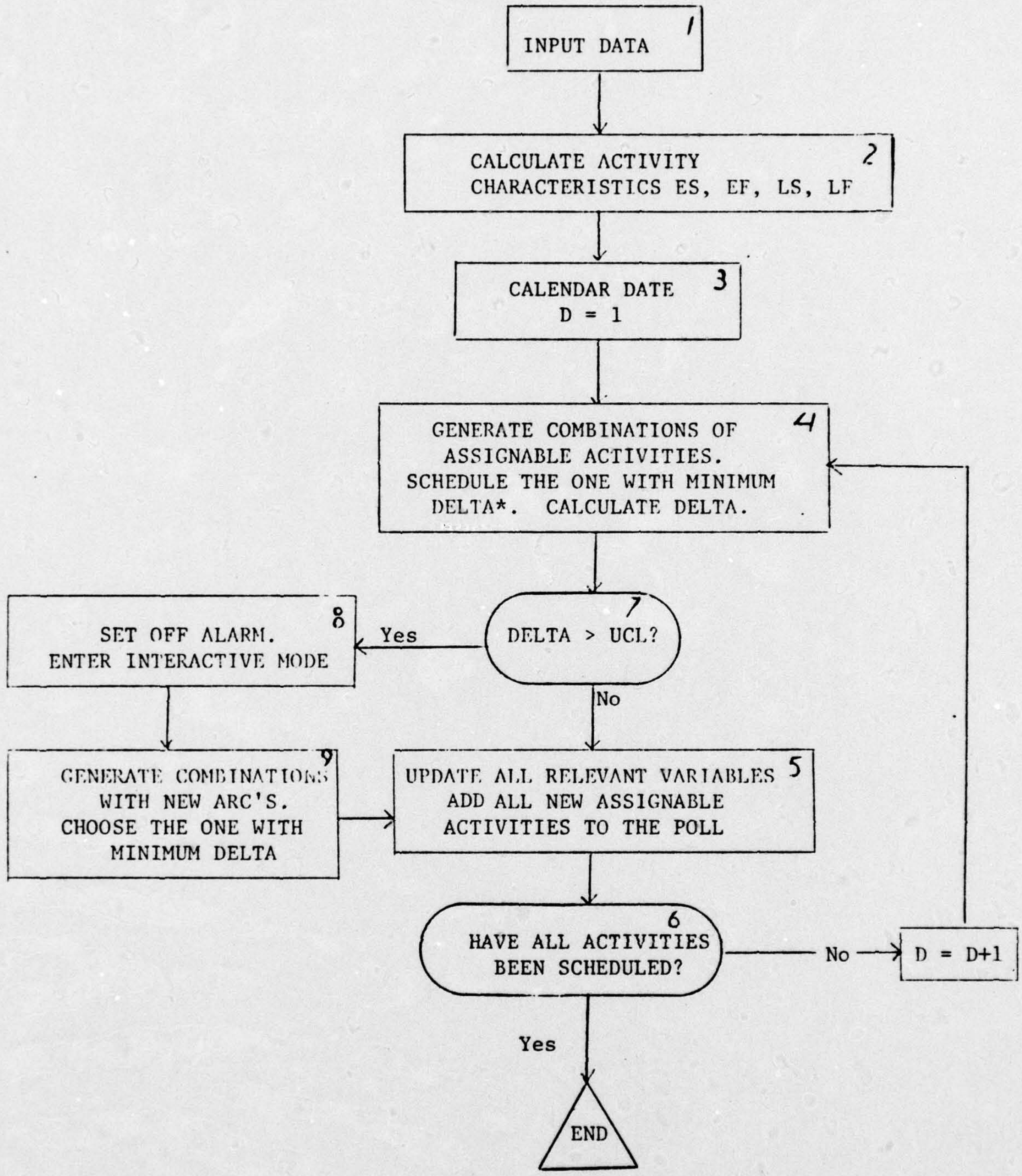


Figure 12. Basic Flow Chart for Scream

Source: Dar-El, Behmoaram, and Tur (1978)

slack for each activity. These items are stored in matrices for further use in the scheduling process.

Block 3 initializes the calendar to day 1.

Block 4 schedules the activities based on the following logic. At the start of each period every activity associated with any of the projects to be scheduled must be in one of the following mutually exclusive sets: (1) activities which have been completed; (2) activities which have been started but have not yet been completed; (3) activities not yet started that have no precedent activities; (4) activities not yet started that have no precedent activities yet to be completed; and (5) activities that cannot be started due to the fact that one or more precedent activities have not yet been completed.

In a given period, activities in sets 2, 3, and 4 are eligible for the assignment of resources. Such activities are referred to as assignable activities. However, resource availabilities will not usually be sufficient to allow all assignable activities to be assigned simultaneously in a given period. This creates the problem of determining which activities should be assigned in any given period.

The assignments made in a given period determine the set of assignable activities for future periods. The minimum cost attainable in any given period will be dependent on the set of assignable activities for that period. This implies that in order to minimize total system cost it will be necessary to account for the impact that the assignments made in a given period have on the costs of future periods. Unfortunately, this will result in a combinatorial problem which is far too large to be solved in a cost effective manner.

In order to avoid this problem Behmoaram utilized a strategy which was first utilized by Weist (1963). This strategy consists of decomposing the multi-period optimization problem into a series of sub-problems, one for each period in the planning horizon, and solving these sub-problems independently. Admittedly, such an approach cannot guarantee to minimize total system cost. Nevertheless this appears to be a resonable approach for dealing with a problem which would otherwise be unsolvable. The sub-problem for each period is solved as follows: (1) a "binary enumeration technique" developed by Dar-El and Tur (1975) is used to generate all possible combinations of assignable activities. This binary enumeration technique uses bit level storage in order to exploit the fact that a computer word in FORTRAN on the IBM 360 contains 32 bits. In addition, the time required to perform logic operations is much less at the bit level than at the word level; (2) the resource requirements for each assignable activity combination is computed and compared to the amounts of the various resources which are available during the period of interest. These combinations which require one or more of the various resources than is available are classified as infeasible and discarded. The remainder of the combinations are feasible; (3) the value of the objective function is computed for each feasible combination of assignable activities; and (4) the minimum value of the objective function for the single period problem is determined by comparing each value computed with the previous minimum value. The new value replaces the previous minimum when the new value is less than the previous minimum. Otherwise, the new value is discarded.

Block 5 is an updating routine which is called when the scheduling process for a given day has been completed. It performs the following operations: (1) reduces the duration for the activities scheduled; (2) decreases the total slack of unscheduled activities by one unit; (3) increases the calendar date by one unit; and (4) removes activities that have been completed from the set of available activities.

Block 6 checks whether or not all activities have been scheduled. Blocks 7, 8, and 9 form a subsystem which permits the model to be used in an interactive mode the need for which is explained below.

The amount of time required to accomplish a given activity will be dependent on the work method used to complete it. For example, tamden-arc automatic welding equipment requires about 25 percent less time than single-arc automatic welding (Mack-Forlist and Newman, 1970). Another example, the amount of time required to fabricate a panel will be dependent on the extent to which assembly line methods are used, the degree to which the assembly line has been balanced, and the priority rules which determine the order in which different types of panels enter the line. The use of a particular work method for a given activity affects not only the time required to complete that activity but the resources which will be available to the other activities. Therefore, it would appear that the tactical shipyard planner should consider alternative work methods. One approach for doing this has been proposed by Wiest (1967) in his SPAR-1 model. This model allows the user to specify three crew sizes: (1) a normal crew size which represents the number of men or other resources typically assigned to the job; (2) a maximum crew

size which represents the number of men required for crashing the job; and (3) a minimum crew size which represents the smallest number of men which can be assigned to the job. Pritsker, Watters, and Wolfe (1969) recognized that certain resources are substitutable and note that such situations can be incorporated into their zero-one integer linear programming model through the use of multiple choice type constraints. Dar-El and Tur (1976) permit the user to specify a number of alternative resource combinations (ARC's) which can be used to accomplish each activity. Behmoaram notes that:

> "If an absolute minimum for the system cost is being sought, then every ARC for all activities should be considered in the scheduling process. However, this would enormously complicate an already complicated combinatorial problem and increase the computation time and cost exponentially....."
> (Behmoaram, 1976, p. 35)

However, he suggests that one way to tackle this problem is "to build a monitoring function into the model which sets off an alarm, requiring the scheduler to investigate the utility of substituting one or more activity ARC's".

The purpose of Block 7 is to perform this monitoring function. This is accomplished by comparing DELTA, minimum cost value of the objective function to an upper control limit. An alarm is set off when the value of DELTA exceeds its upper control limit as indicated by Block 8. When the alarm occurs the scheduler should attempt to identify

new ARC's. The model will be rerun with each of these new ARC's and the one with the minimum value of DELTA will be utilized. This is an interactive process which is indicated by Block 9.

The strategy of generating ARC's is likely to require non-trivial amounts of engineering time. Therefore, it is likely to be expensive. Therefore, postponing the generating of ARC's until an alarm occurs is appealing from the standpoint of saving engineering time. This advantage is offset somewhat by the necessity of having to make multiple runs which will increase computation cost. In addition the problem of how to determine the value of the upper control limit has not been answered satisfactorily.

Phase 3: Specification of Solution Procedure

The tactical shipyard planning problem is to minimize the sum of the following cost:

(1) cost of productivity lost as a result of splitting activities;

(2) cost of overtime premiums;

(3) cost of project lateness;

(4) cost of productivity lost as a result of intertrade interference;

(5) cost of productivity lost as a result of intratrade interference;

(6) cost of disruption resulting from late deliveries of materials subject to the following constraints:

1. resource availabilities cannot be exceeded;
2. no activity can be started until all of its precedent

requirements have been met.

In theory this problem could be formulated as a zero-one integer linear programming problem. However, Lenstra (1976) as reported by Elmaghraby (1977, p. 217) has shown that

> The problem of scheduling activities on multiple resources when the activities are subject to precedence constraints and the availability of resources is limited is known to be "NP hard".... This implies that, in all probability, there shall be no "efficient" algorithm for solving this problem (in the sense of achieving optimality).

This implies that the tactical shipyard planning problem is "NP hard". This indicates that a search for an analytic procedure for solving the problem would not likely be fruitful. Thus it was decided not to consider analytic methods further. This left only two options for attacking the problem: (1) heuristic procedures; or (2) branch and bound theory.

The branch and bound approach is a systematic procedure whereby each point in the entire space of feasible solutions is enumerated either explicitly or implicitly. It is desirable to minimize the number of points that have to be enumerated explicitly. Three techniques are used to accomplish this: (1) dominance; (2) feasibility; (3) redundancy. However, Baker (1974, p. 276-277) has noted

> Unfortunately, all implicit enumeration approaches to the determination of an optimal schedule appear to be susceptible to the combinatorial nature of these problems when they are tested on the large versions typically found in practice.... there is no evidence that such techniques can reliably handle multi-resource versions of a problem that contains more than 50 activities.

Thus it was decided not to consider branch and bound methods as candidates for the solution procedure. This left heuristic procedures as the only viable option for attacking the tactical shipyard planning problem.

A review of heuristic models published in the open literature revealed that none of the heuristic approaches to the mrmp scheduling problems published in the open literature with the exceptions of a model developed by Dar-El, Behmoaram and Tur (1978) utilized a cost based objective function. The heuristic use in Levy, Thompson and Wiest (1963) was designed to reduce peak resource requirements and smooth out period-to-period assignments subject to a constraint on project duration. SPAR-1 (Wiest, 1967) utilizes a heuristic which places primary emphasis on completing the job as early as possible. RAMPS which was developed for proprietary use utilizes a heuristic which involves minimizing a weighted function of variables such as total slack, idle resources, project delay cost, and number of successors to a given job (Lambourne, 1963; Moshman, Johnson and Laresen, 1963; Wiest, 1963; and Wiest, 1969).

Jennett (1970) lists a number of other network analysis programs which are commercially available but for which the scheduling heuristics are kept secret.

The model considered by Dar-El, Behmoaram and Tur (1978) was to minimize the sum of the following costs.

(1) cost of productivity lost as a result of splitting activities;

(2) cost of overtime premiums;

(3) cost of project lateness; and

(4) total cost of idle resources;

subject to the following constraints:

(1) resource availabilities cannot be exceeded; and

(2) no activity can be started until all of its precedent requirements have been met.

Note that this problem differs from the tactical shipyard planning problem in that it does not consider the following costs:

(1) cost of intertrade interference;

(2) cost of intratrade interference;

(3) cost of carrying additional material inventories to protect against late deliveries; and

whereas the tactical shipyard planning problem does. Another difference is that the Dar-El, Behmoaram and Tur (DBT) model includes the cost of idle resources in their objective function whereas the tactical shipyard planning problem does not. The reason for not including this cost in the tactical shipyard planning model is that such costs are primarily determined by the size of each trade's workforce. Another difference is that the DBT model assumes that the resource level is constant for all time periods. In the tactical shipyard planning problem it is possible to vary resource levels from period to period. These variables are specified by strategic

level management. Therefore, it is not reasonable to have these costs in the tactical shipyard planning model. However, the tactical shipyard planning model does report the percentage of idle time of each resource to the strategic level planner who evaluates this cost with that of changing appropriate resource levels. The DBT model was modified to handle this by removing the cost of idle resources from the objective function and modifying the output procedure so that this variable could be printed out separately.

A special procedure had to be developed for handling intertrade interferences. This procedure consisted of the following steps:

(1) put all activities in the following categories into a scheduling pool:

(a) activities which have been started but have not yet been completed;

(b) activities not yet started that have no precedents; and

(c) activities not yet started for which all precedents have been completed.

This is illustrated by Figure 13 which graphically depicts the composition of the scheduling pool.

(2) partition the scheduling pool into:

(a) an interference free subset which contains those activities which can be performed with any other member of the subset without creating interference;

(b) a number of mutually exclusive interference subsets such that the activities within a given interference subset interfer with one another, while activities in different

Scheduling
pool

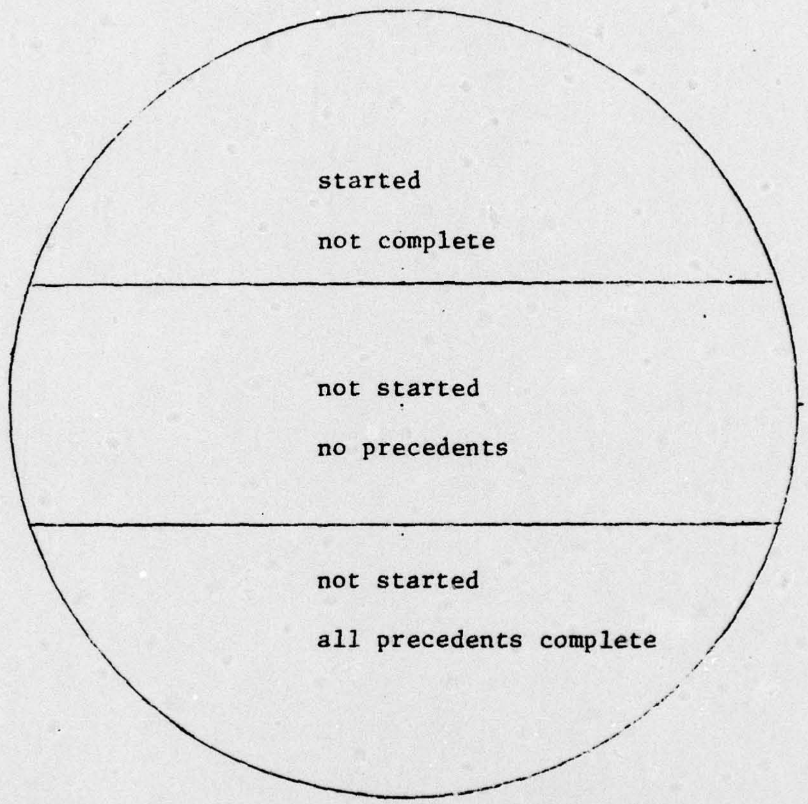


FIGURE 13 . Composition of scheduling pool.

subsets do not.

This is illustrated by Figure 14 which depicts the partitioning of the scheduling pool into an interference free subset and n interference subsets. The activities in each interference subset cannot be performed simultaneously with another member of the same set without creating interference. However, any combination of activities consisting of all activities in the interference free subset and at most one activity from the n interference can be performed simultaneously without creating interference.

(3) find all possible combinations of activities which consists of one member from each of the mutually exclusive interference subsets and all of the activities in the interference free subset;

This is illustrated by Figure 15 which shows all possible combinations of activities which can be formed when the interference subset consists of activities A, B, and C; the first interference subset consists of D and E; and the second interference subset consists of F and G.

(4) calculate resources required for each combination of activities, compare resource requirements with resource availability levels, and eliminate infeasible combinations;

(5) calculate value of objective function for each feasible resource combination and keep combinations which minimize value of objective function for that period.

The logic for dealing with intertrade interference is to first attempt to schedule the activities without intertrade interference. If all projects can be completed by their respective due dates then the interference free solution will dominate any solution which has interference. However, if lateness results, then the scheduler should

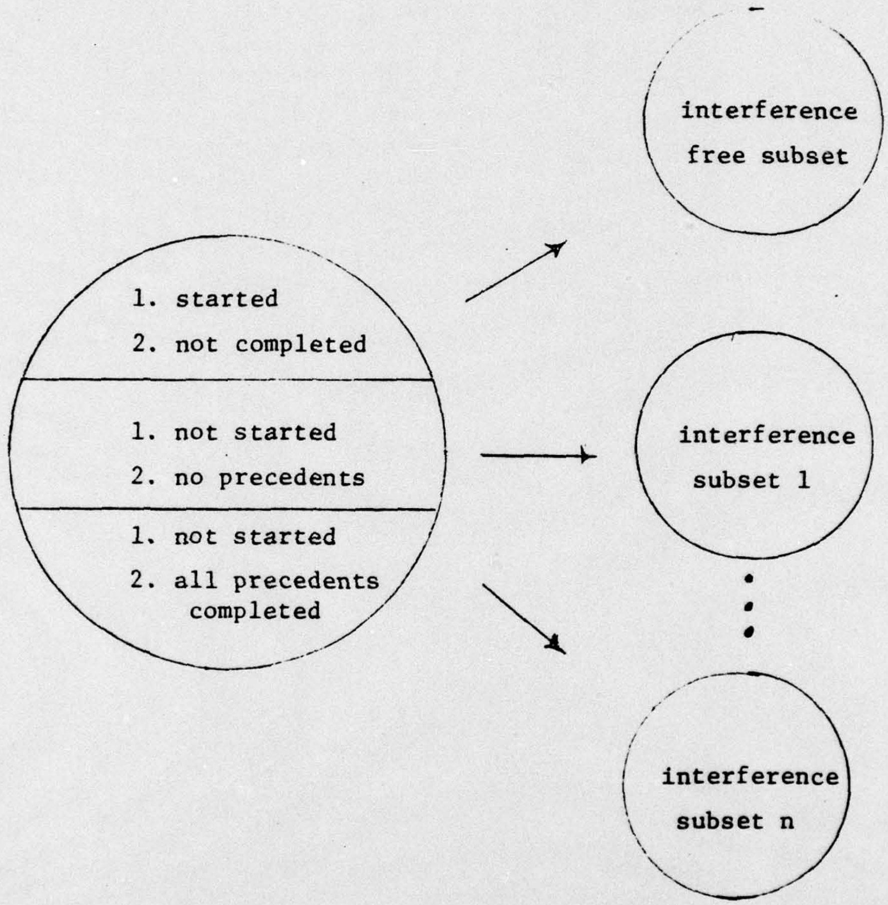


FIGURE 14. Partitioning of scheduling pool into interference free subset and n interference subsets.

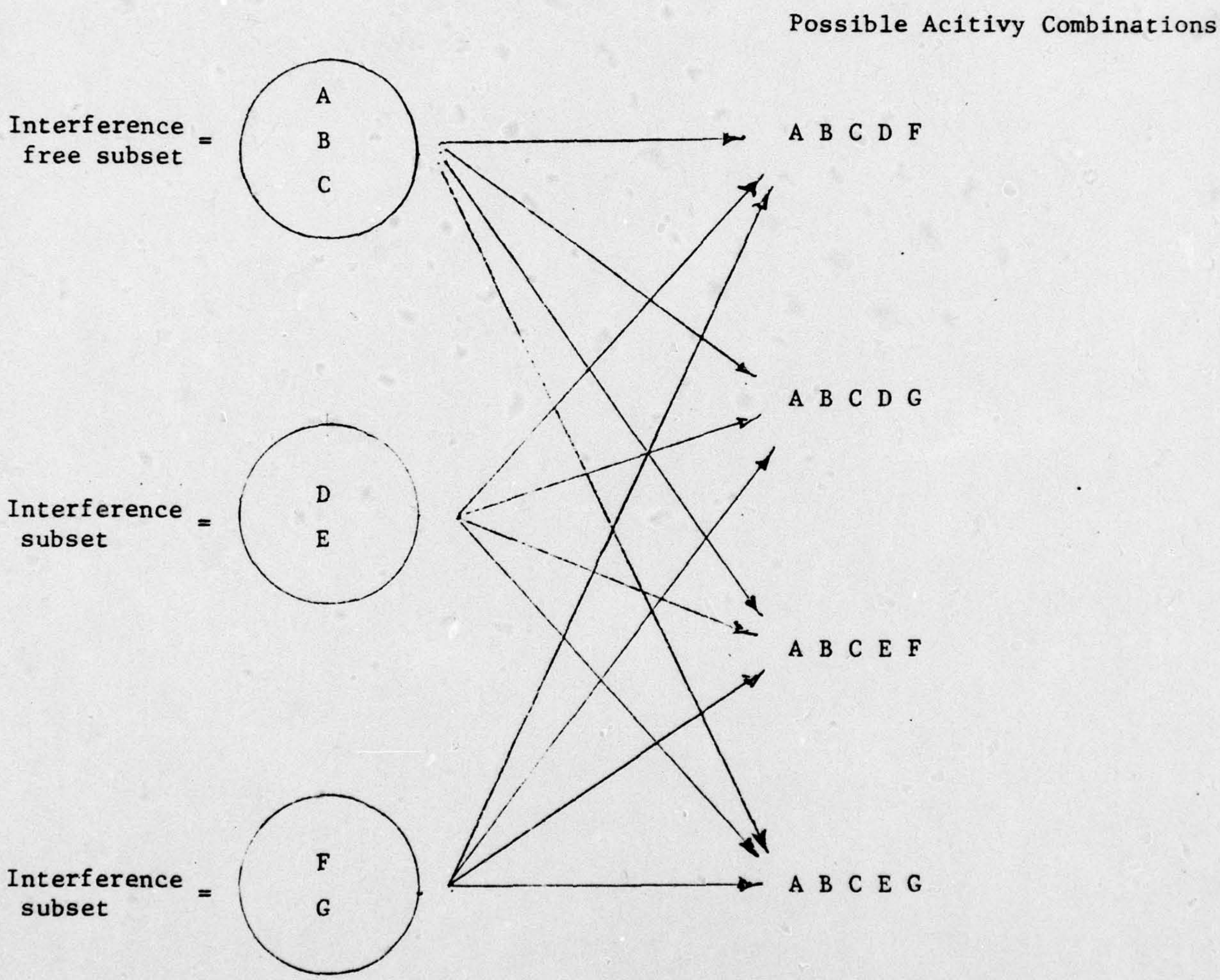


FIGURE 15. Formation of all possible interference free combinations of activities where D and E interfere and F and G interfere.

selectively permit intertrade interference to arise. This is accomplished by removing the constraint that specifies that two activities cannot be performed together and increasing the times required to perform the activities.

Intratrade interference can be handled by rerunning the model for each crew size which can be used to perform an activity. In doing this it will be necessary to adjust the activity duration times to account for the effects of diminishing returns which result from intratrade interference and the cost of performing the activity to reflect the size of the crew.

The cost of late deliveries of materials can be handled by regarding the arrival of a material as an activity and calculating the lateness penalty for that activity. In this case the penalty function will be the expected cost of lateness caused by material shortages which corresponds to the various values of delivery lead time.

An example will be presented to illustrate the logic for specifying the lateness penalty function and the associated incremental inventory carrying cost function.

EXAMPLE. The main engine is to be built by a subcontractor. If the engine is not delivered in time to be installed prior to launch, then an additional cost of installation equal to C_D will be incurred. Let t_ℓ represent the latest date for delivery of the engine which will permit it to be installed prior to launch. If the shipyard specifies a delivery date of t_ℓ then there will be a 50 percent chance of receiving delivery on time, 33.3 percent chance of being one period late, and a 16.7 percent chance of being two periods late. The shipyard has to

pay M dollars for the engine on delivery. If the delivery date denoted by t_d is specified to equal t_ℓ, then there will be a 50 percent chance that delivery will be at least one period late. The expected cost of late delivery will be $.5\ C_D$. If t_d is specified to equal $t_{\ell-1}$, then the expected cost of late delivery will be $.167\ C_D$. However, there will be a 50 percent chance that the engine will be delivered one period early. If this occurs, then the shipyard will incur an opportunity cost of iM dollars where i represents the shipyards cost of capital. The expected opportunity loss will be .5 iM. If t_d is specified to equal to $t_{\ell-2}$, then there will be a zero percent chance of late delivery. However, there will be a 50 percent chance of receiving delivery two periods early and a 33.7 percent chance of receiving delivery one period early. The expected opportunity loss will be equal to $.5\ (2i + i^2)\ M + .337\ iM$.

The lateness penalty function and the inventory carrying cost function for the above situation is shown in Figure 16.

Phase 4: Development of Computer Programs

A list of an experimental computer program for solving the tactical shipyard planning model is contained in Appendix A.

	Charges for Period	
Delivery Date Specified	Lateness Penalty	Incremental Inventory Carrying Case
$t_{\ell-2}$	0	$[.5(2i+i^2)+.337i]m-.5im$
$t_{\ell-1}$	$.167C_D$	$.5im$
t_{ℓ}	$(.5-.167)C_D$	0
$t_{\ell+1}$	$(1-.5)C_D$	0
$>t_{\ell+1}$	0	0

FIGURE 16. Lateness penalty function and inventory carrying cost function.

BIBLIOGRAPHY

BIBLIOGRAPHY

Anthony, R. N., Planning and Control Systems: A Framework for Analysis, Harvard Business School, Boston, 1965.

Baker, Kenneth R. Introduction to Sequencing and Scheduling. New York: John Wiley and Sons, Inc., 1974.

Behmoaram, A. "Multi-project scheduling with limited resources", Unpublished M.Sc. thesis, Technion - I.I.T., Haifa, October 1976.

Bennington, G. E. and L. F. McGinnis. "A critique of project planning with constrained resources", in S. E. Elmaghraby (ed.), Symposium on Theory of Scheduling and Its Applications, New York: Springer-Verlag, 1973, pp. 1-28.

Clark, Charles E., "The greatest of a finite set of random variables", Operations Research, 1961, 9(2), 146-162.

Corporate-Tech Planning, Inc. Production Oriented Planning: A Manual on Planning and Production Control for Shipyard Use. Portsmouth, N.H.: Corporate-Tech Planning, Inc., 1978.

Crowston, W. O. and G. L. Thompson, "Decision CPM: A method for simultaneous planning, scheduling and control of projects", Operations Research, 1967, 15(3), 407-426.

Dar-El, E. M., A. Behmoaram, and Y. Tur, "SCREAM-Scarce Resource Allocation to Multi-Projects", Project Management Quarterly, 1978.

Dar-El, E. M. and Yigal Tur. "A multi-resource project scheduling algorithm", AIIE Transactions, 1977, 9(1), 44-52.

Dar-El, E. M. and Y. Tur. "Resource allocation of a multi-resource project for variable resource availabilities", AIIE Transactions, 1978, 10(3),

Davis, E. W., "Project scheduling under resource constraints-historical review and categorization of procedures", AIIE Transactions, 1973, 5, 297-313.

Davis, E. W. and Patterson, J. H., "A comparison of heuristics and optimum solutions in resource-constrained project scheduling", Management Science, 1975, 21(8), 944-955.

Elmaghraby, Salah E. Activity Networks: Project Planning and Control by Network Models. New York: John Wiley and Sons, Inc., 1977.

Fendley, L., "Towards the development of a complete multi-project scheduling system", Journal of Industrial Engineering, 1968, 19(10), 505-515.

Frisch, F. A. P. Production and Construction: A Comparison of Concepts in Shipbuilding and Other Industries. Washington, D. C.: U. S. Department of the Navy, 1976.

Frisch, F. A. P. Personal communication, 1979.

Geoffrion, Arthur, "Elements of large-scale mathematical programming", Management Science, 1970, 16(11) 652-691.

Gonguet, L., "Comparison of three heuristic procedures for allocating resources and producing schedule", in Project Planning by Network Analysis, Lombaers, H. J. M. (Ed.), North Holland, Amsterdam, 1969.

Hancock, Walton M., "The learning curve", in Industrial Engineering Handbook, H. B. Maynard (Ed.), New York: McGraw-Hill, 1971, pp. 7-113.

Herroelen, W. S., "Resource constrained project scheduling--the state of the art", Operational Research Quarterly, 1973, 23(2), 261-275.

Jennett, E., "Availability of CPM Programs", Project Management Quarterly, 1970, 10-13.

Lambourne, S., "Resource allocation and multiproject scheduling (RAMPS) -- A new tool in planning and control", The Computer Journal, 1963, 5, 300-304.

Lasdon, Leon S., "Large Scale Programming", in Moder, Joseph J. and Elmaghraby, Salah E., Handbook of Operations Research Models and Applications, Volume 2, New York, Van Nostrand Reinhold Company, 266-294.

Lenstra, Jan Karel. Sequencing by enumerative methods. Unpublished Ph.D. dissertation, University of Amsterdam, Holland, 1976.

Levy, F. K., Thompson, G. L., and Wiest, J. J., "Multi-ship, multi-shop, workload smoothing program", Naval Research Logistics Quarterly, 1962, 9(1), 37-44.

McMichael, David, and Orleans, B. S. TRANSIM-A General Purpose Problem Solving Tool, 1975.

Mack-Forlist, Daniel M. and Newman, Arthur. The Conversion of Shipbuilding from Military to Civilian Markets. New York: Praeger Publ., 1970.

Mark Battle Associates, Inc. Shipbuilding Manpower Study: Executive Summary. Washington, D. C.: Mark Battle Associates, Inc., 1974.

MacCrimmon, K. R. and Ryavec, C. A., "An analytical study of PERT assumptions", Operations Research, 1964, 12(1), 16-37.

McGee, A. A. and Markarian, M. D., "Optimum allocation of research/engineering manpower within a multi-project organizational structure", IRE Trans. Engineering Management, 1962, EM9, 104-108.

Millen, William, "Some aspects of shipyard productivity", paper presented to Pacific Northwest Section, the Society of Navy Architects and Marine Engineers, February, 1978.

Moder, J. J. and Phillips, C. R. Project Management with CPM and PERT, 2nd ed. New York: Van Nostrand Reinhold Co., 1970.

Moshman, M., Johnson, I., Larsen, M., "RAMPS--A technique for resource allocation and multi-project scheduling", Proceedings Spring Joint Computer Conference, 1963.

Orchard-Hays, W., "On the Proper Use of a Powerful MPS", in Cottle, R. W. and Krarup, Optimization Methods, New York: Crane, Ruscak and Co. Inc. 1974.

Pascoe, T. L.,"Heuristic method for allocating resources", Ph.D. dissertaion, University of Cambridge, 1965.

Patterson, J. H., "Alternate methods of project scheduling with limited resources", Naval Research Logistics Quarterly, 1973, 20(4), 767-784.

Patterson, J. H. and Huber, W. D., "A horizon-varying, zero-one approach to project scheduling", Management Science, 1974, 20(6), 990-998.

Pritsker, A. A. B., Q-GERT: GERT Networks with Queueing Capabilities, Purdue University, Lafayette, Ind., Research Memorandum, 72-7, December, 1972.

Pritsker, A. A. B., Watters, L. J., and Wolfe, P. M., "Multi-project scheduling with limited resources: A zero-one programming approach", Management Science, 1969, 16(1), 93-109.

Tippett, L. H. C., "On the extreme individuals and the range of samples taken from a normal population", Biometrika, 1925, 17, 364-377.

Terry, W. R., Green, F., and Magnuson, A. Confidential survey of U. S. shipyards conducted by the Industrial Engineering/Operations Research Department at Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 1979.

Wiest, J. D., "The scheduling of large projects with limited resources", Ph.D. dissertation, Carnegie Institute of Technology, 1963.

Wiest, J. D., "A heuristic model for scheduling large projects with limited resources", Management Science, 1967, 13(6), B359-B377.

Wiest, J. D., "A heuristic scheduling and resource allocation model for evaluating alternative weapon system programs", RAND Corp. Report No. RM-5769-RP, 1969.

Wiest, Jerone D. and Levy, Ferdinand K. A Management Guide to PERT/CPM with GERT/PDM/DCPM and other Networks. Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1977.

APPENDIX A

Listing of Computer Program for Solving

the Tactical Shipyard Planning Problem.

```
$JOB WATFIV,TIME=200,PAGES=20
C                    ////////////////////////////////////////////
C                    //                                        //
C                    //       MULTIPROJECT SCHEDULING          //
C                    //                                        //   1608
C                    //       WITH LIMITED RESOURCE            //   VFI&SU
C                    //            INCOMPATIBLE ACTIVITIES     //
C                    //            RESOURCE LEVELING           //
C                    //            KEY ACTIVITIES TARGET DATE  //
C                    //                                        //
C                    ////////////////////////////////////////////
C
C
C
C   PROGRAM INPUT:
C
C   1. FIRST CARD         1- 5 = NUMBER OF PROJECTS
C   2. PP CARD            1- 2 = PP OR ANY OTHER CHARACTERS
C                         3- 5 = PROJECT NUMBER
C                         6-10 = ARRIVING DATE
C                        11-15 = NUMBER OF ACTIVITIES
C                        16-20 = CRITICAL SLACK
C                        21-25 = LATENESS PENALTY
C                        26-30 = DUE DATE
C   4. KEY ACTIVITY CARDS
C                         1- 5 = 99999
C                         6-10 = ACTIVITY NUMBER
C                        11-15 = TARGET COMPLETION DATE
C   5. BLANK CARD
C   REPEAT 2,3,4,5 FOR EACH PROJECT
C   6. ACTIVITY INFORMATION
C   6.1                   1- 2 = PP OR ANY OTHER CHARACTERS
C                         3- 5 = PROJECT NUMBER
C   6.2                   1- 5 = ACTIVITY NUMBER
C                        11-15 = RESOURCE 1
C                        16-20 = RESOURCE 2
C                        21-25 = RESOURCE 3
C                        26-30 = RESOURCE 4
C                        31-35 = RESOURCE 5
C                        36-40 = ACTIVITY DURATION
C   REPEAT 6 FOR EACH PROJECT
C   7. RESOURCE LEVEL
C                         1- 5 = RESOURCE NUMBER
C                         6-10 = UNITS AVAILABLE
C                        11-15 = FROM DATE
C                        16-20 = TO DATE
C   REPEAT 7 FOR EVERY RESOURCE CHANGE
C   8. SEPARATE CARD      1- 5 = 99999
C   9. OVERTIME INFORMATION   5F6.2
C  10. COST OF RESOURCE 5I5
C  11. SPLITTING PENALTY
C  12. FACTOR OF OVER TIME COST 5F6.2
C  13. INCOMPATIBLE ACTIVITIES SETS
C      ONE CARD FOR EACH SET   5I5
C  14. END CARD           1- 5 =     0
C
C
  1         IMPLICIT INTEGER (A-Z)
```

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
      REAL CR(5),VCCT(5)
      INTEGER ACCH(10,100,5),CRIP(10),SA(250),COMP(100),NIMP(10,100),
     1 PSA(32),ICCMS(32,2),CCCMS(32,5),FR(5),KA(5),CI(5),SI(10),
     2 NSAP(32),CSLK(10),CS(5),LP(10),USACH(32),VP(32),SPEN(5),LCCMS(32)
      INTEGER NCOM(10),TRR(5),COMPL(10),CAC(32),KAICT(5),CHK(100)
      DIMENSION IYF(10,100,5),N(10),ARRD(10),SIK(10,100,6),TSAV(10,100),
     1 KK(5),TCTWF(5),OTWR(5),DD(10),LFS(10),ANCTU(5),TNUTU(5),NOTU(5)
     2,TP(6),KATD(30,2)
      REAL DEL,MINDEL,TCCT,U,ADEL,T,RDEL,SQRT,X,Z,CF(5),CCT(5)
      INTEGER H,S
C
C   READ NUMBER OF PROJECTS
C   N(H) : NUMBER OF ELEMENTS OF PROJECT H.
C   CSLK:  CRITICAL SLACK.
C   LP :   LATENESS PENALTY
C   DD :   DUE DATE
C   KATD(T,I) : KEY ACTIVITY TARGET DATE
C          I=1 : KEY ACTIVITY
C          I=2 : TARGET DATE
C
      II=1
      S=0
      WRITE(6,611)
  611 FORMAT(1H1,19X,'/////////////////////////////////////////////////',/
     1,20X,       '//                                              //',/,
     220X,        '//          MULTIPROJECT SCHEDULING             //'
     3,/,20X,     '//                                              //',/,
     420X,        '//////////////////////////////////////////////////',/,
     520X,        '//                                              //',/,
     620X,        '//                PROGRAM OUTPUT                //',/,
     720X,        '//                                              //',/,
     820X,        '//////////////////////////////////////////////////',///)
      DO 10 H=1,10
   10 N(H)=0
C
C   READ NUMBER OF PROJECTS
C
      READ(3,500)S
  500 FORMAT(I5)
      DO 2 HH=1,S
C
C   READ PROJECT NUMBER,ARRIVAL DATE,NUMBERS OF ACTIVITIES, CRITICAL
C   SLACK, LATENESS PENALTY AND DUE DATE
C
      READ(3,501)A,B,C,D,E,F,G
      ARRD(B)=C
      N(B)=D
      CSLK(B)=E
      LP(B)=F
      DD(B)=G
  501 FORMAT(A2,I3,5I5)
      WRITE(6,601)B,ARRD(B),N(B),DD(B),CSLK(B),LP(B)
  601 FORMAT(//,10X,' PROJECT',I4,' ARRIVED ON DATE',I4,' HAS',I4
     1,' ACTIVITIES AND DUE DATE',I4,/,23X,'CRITICAL SLACK IS',I5,
     2' UNITS  AND LATENESS PENALTY IS',I5,' UNITS',/)
      H=B
      IF(H.LT.1)GO TO 3
      WRITE(6,701)
  701 FORMAT(//,10X,12H ACTIVITY NO,'   IMP 1 ','   IMP 2    IMP 3 ',
     1 '    IMP 4    IMP 5 ',/)
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
   25 CONTINUE
   26 CONTINUE
   30 CONTINUE
   31 IF((IE.EQ.0).AND.(IG.EQ.0))GO TO 35
      IF(IG.EQ.0)GO TO 32
      IF(IE.EQ.0)GO TO 33
      B=VP(IE)
      PSA(B)=CAC(IG)
      IE=IE-1
      IG=IG-1
      GO TO 31
   32 B=VP(IE)
      PSA(B)=PSA(NN).
      NN=NN-1
      IE=IE-1
      GO TO 31
   33 NN=NN+1
      PSA(NN)=CAC(IG)
      IG=IG-1
      GO TO 31
   35 CONTINUE
C
C  THE TOTAL SLACK OF UNSCHEDULED ACT IS UPDATED
C
      IF(JC.EQ.0)GO TO 45
      DO 40 IJ=1,JC
      H=USACH(IJ)/1000
      I=USACH(IJ)-H*1000
   40 ACCH(H,I,5)=ACCH(H,I,5)-1
   45 DO 50 IL=1,NACC
      LCOMB(IL)=CCOMB(IL,1)
   50 CCOMB(IL,1)=0
      NALC=NACC
      RETURN
      END
CP
C
C
      SUBROUTINE STATIS(S,N,TRR,RA,CD,CS,COMPD,ARRD,CRIP,DD,ANDTU)
C  COLLECT STATISTICS:
C        1. PERCENTAGE OF RESOURCE ULTILIZATION.
C        2. OVERTIME WORK OF RESOURCE.
C        3. WEIGHTED PERCENTAGE UTILIZATION.
C        4. PROJECT DURATION.
C        .5. PROJECT TARDINESS.
      IMPLICIT INTEGER(A-Z)
      INTEGER N(10),TRR(5),RA(5),CS(5),COMPD(10),ARRD(10),CRIP(10),
     1 DD(10),ANDTU(5)
      SUM=0
      ADD=0
      TTARD=0
      WRITE(6,10)
   10 FORMAT(1H1,19X,'************************************',/,20X,
     1                '**    STATISTICS OF THE SCHEDULE    **',/,20X,
     2                '************************************',/)
      DO 20 J=1,S
      PER=((TRR(J)-ANDTU(J))*100)/((CD-1)*RA(J))
      SUM=SUM+(PER*CS(J))
      ADD=ADD+CS(J)
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
      DEL=ILPEN+TCIR+ISPEN+TCOT
      IF(MINDEL.LT.DEL)GO TO 25
      MINDEL=DEL
      G=TCIR
      R=TSPEN
      P=RILP
      T=TCOT
      PDEL=G+R+P+T
      LAPR=0
      STO1=0
      STO2=0
      DO 65 H=1,S
      STO1=ST(H)*LP(H)
      IF(STO1.LE.STO2)GO TO 65
      STO2=STO1
      LAPR=H
   65 CONTINUE
      DO 67 L=1,5
   67 TCTWR(L)=0
      DO 68 L=1,5
      TNCTU(L)=NCTU(L)
   68 TCTWR(L)=CTWR(L)
      NACC=IIMX
      COT1=CTI
      DO 70 JA=1,NACC
      CCOMB(JA,1)=ICOMB(JA,1)
   70 CCOMB(JA,2)=ICOMB(JA,2)
   25 CONTINUE
      IF((III.NE.0).AND.(K.GT.1))GO TO 1000
C
C     CHECK KEY ACTIVITIES TARGET DATE
C
      IF(TT.EQ.0.)GO TO 201
      DO 101 JA=1,NACC
      DO 101 J=1,TT
      IF(CCOMB(JA,1).NE.KATD(J,1))GO TO 101
      IF(CD.LE.KATD(J,2))GO TO 101
      WRITE(6,601)(KATD(J,I),I=1,2)
  601 FORMAT(//,10X,' **** KEY ACTIVITY',I5,' CAN NOT MEET TARGET DATE
     1',I4,' ****',/,5X,'SUGGEST TO EXPAND THE RESOURCE AVAILABLE,
     2 OR INPUT INTERFERENCE PENALTY FOR INCOMPATABLE ACTIVITIES')
      RETURN
  101 CONTINUE
  201 CONTINUE
      ADEL=ADEL+PDEL
      ATCIR=ATCIR+G
      ATLPEN=ATLPEN+P
      ATSPEN=ATSPEN+R
      ATCOT=ATCOT+T
      DO 72 L=1,5
   72 ANOTU(L)=ANOTU(L)+TNCTU(L)
      JC =0
      DO 71 JB=1,NN
      IF(NSAP(JB).EQ.0)GO TO 71
      JC=JC+1
      USACH(JC)=PSA(JB)
   71 CONTINUE
      NACC1=NACC
      NACC2=0
      IF(NACC1.LE.11)GO TO 274
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
      NACC1=11
      NACC2=NACC-11
  374 WRITE(6,75)CD,(CCOMB(JA,1),JA=1,NACC1)
   75 FORMAT(/,10X,' *** THE FOLLOWING ACT HAVE BEEN SCHE ON DATE',
     1 I5,' :',11I6)
      WRITE(6,375)(CCOMB(JA,1),JA=1,NACC1)
      WRITE(6,375)(CCOMB(JA,1),JA=1,NACC1)
  375 FORMAT(1H+,61X,11I6)
      IF(NACC2.EQ.0)GO TO 378
      WRITE(6,376)(CCOMB(JA,1),JA=11,NACC2)
  376 FORMAT(11X,20I6)
      WRITE(6,377)(CCOMB(JA,1),JA=11,NACC2)
      WRITE(6,377)(CCOMB(JA,1),JA=11,NACC2)
  377 FORMAT(1H+,10X,20I6)
  378 WRITE(6,77)PDEL,C,R,P,T
   77 FORMAT(10X,' DELTA=',F9.2,/,10X,' TCIR=',F10.2,/,10X,' TSPEN=',I6,
     1/,10X,' TLPEN=',I6,/,10X,' TCOT=',F10.2)
      IF(CCT1.EQ.0)GO TO 759
      WRITE(6,76)(TCTWR(L),L=1,CCT1)
   76 FORMAT(10X,' THE FOLLOWING RESOURCES WORK OVERTIME:',5I4)
  759 CONTINUE
      IF(INCOMP.EQ.0)GO TO 804
      DO 801 L=1,NN
  801 PSA(L)=PPSA(L)
      DO 803 JA=1,NACC
      DO 802 L=1,NN
      IF(CCOMB(JA,1).NE.PPSA(L))GO TO 802
      CCOMB(JA,2)=L
      GO TO 803
  802 CONTINUE
  803 CONTINUE
  804 INCOMP=0
   74 CALL UPDATE(ARRD,NIMP,PSA,CCOMB,GIK,USACH,ACCH,NN,NACC,N,S,
     1 IC,IB,IMF,CD,JC,NALC,LCOMB,CCMPD,NCOM)
      IF(NN.EQ.0)GO TO 80
      GO TO 11
   80 WRITE(6,78)
   78 FORMAT(////,20X,'//////////////////////////////////////////',/,
     120X,              '//                                      //',/,
     220X,              '//        END OF SCHEDULE               //',/,
     320X,              '//                                      //',/,
     420X,              '//////////////////////////////////////////',/,1H1)
      WRITE(6,85)
   85 FORMAT(///,20X,' **** EFFICIENCY OF SCHEDULE ******',///)
      RLPEN=0
      RADEL=ADEL-ATLPEN
      DO 799 I=1,S
      LATE=COMPD(I)-DD(I)-1
      IF(LATE.LE.0)GO TO 799
      RLPEN=RLPEN+LATE*LP(I)
      RADEL=RADEL+RLPEN
  799 CONTINUE
      WRITE(6,79)ADEL,RADEL,ATCIR,ATCIR,ATSPEN,ATSPEN,ATLPEN,RLPEN
     1,ATCOT,ATCOT
   79 FORMAT(///,23X,'AARTIFICIAL',9X,'REAL',//,10X,' ACC DEL= ',2F15.2
     1,/,10X,' ACC CIR= ',I12,I15,/,10X,' ACC SP:ULPEN= ',I8,I15,/,10X,
     2'ACCOUU ACC LPEN=',2I15,/,10X,' ACC COST OVTM= ',F8.2,F15.2)
      RETURN
      END
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
C
C
      SUBROUTINE UPDATE(ARRD,NIMP,PSA,CCOMB,QIK,USACH,ACCH,NN,NACC,N,S,
     1 IC,IE,IMP,CD,JC,NALC,LCOMP,COMPD,NCOM)
      IMPLICIT INTEGER (A-Z)
      INTEGER ARRD(10),NIMP(10,100),PSA(32),CCOMB(32,2),QIK(10,100,6),
     1 VP(32),USACH(32),ACCH(10,100,5),IMP(10,100,5),N(10),LCOMB(32),
     2 NCOM(10),COMPD(10),CAC(32)
      INTEGER IA,IB,IC,ID,IF,IE,IG,IH,IJ,A,B,I,H,NN,NACC,M,S,CD
      IE=0
      IG=0
      DO 1 IA=1,32
      CAC(IA)=0
    1 VP(IA)=0
      CD=CD+1
C
C  ACTIVITIES OF NEWLY ARRIVED PROJECTS ARE ADDED TO THE POOL
C
      DO 20 IA=1,S
      IF(ARRD(IA)-CD)20,15,20
   15 M=N(IA)
      DO 16 IB=1,M
      IF(NIMP(IA,IB).NE.0)GO TO 16
      NN=NN+1
      PSA(NN)=IA*1000+IB
   16 CONTINUE
   20 CONTINUE
C
C   THE DURATION OF SCHEDULED ACTIVITIES IS UPDATED
C
      DO 30 IC=1,NACC
      H=CCOMB(IC,1)/1000
      I=CCOMB(IC,1)-1000*H
      QIK(H,I,6)=QIK(H,I,6)-1
      IF(QIK(H,I,6).NE.0)GO TO 30
      IA=CCOMB(IC,2)
      PSA(IA)=0
C
C  IF ALL ACTIVITIES OF A PROJECT FINISHED INFORMATION SUPPLIED
C
      NCOM(H)=NCOM(H)+1
      IF(NCOM(H).NE.N(H))GO TO 28
      J=CD-1
      COMPD(H)=J
      WRITE(6,27)H,J
   27 FORMAT(' ******** PROJECT',I6,'  HAS BEEN TERMINATED ON DATE',I4)
   28 CONTINUE
      IE=IE+1
      VP(IE)=CCOMB(IC,2)
C
C  ACTIVITIES WHOSE ALL IMME. PREDE. ARE FINISHED ARE ADDED TO THE POOL.
C
      DO 25 IF=1,5
      A=IMP(H,I,IF)
      IF(A.EQ.0)GO TO 26
      NIMP(H,A)=NIMP(H,A)-1
      IF(NIMP(H,A).NE.0)GO TO 25
      IG=IG+1
      CAC(IG)=H*1000+A
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
 200  IF(III.NE.0)GO TO 212
      WRITE(6,15)(PSA(JA),JA=1,N1)
  15  FORMAT(///,10X,' *** POOL OF SCHE ACT CONTAINS: ',12I5,/,' ',20I5)
 212  MM=2**N1-1
      DO 25 KK=1,MM
      KA=KK
      ADD=0
      KC=KK
  17  FF=KC-(KC/2)*2
      KC=KC/2
      IF((FF.EQ.0).AND.(KC.EQ.0))GO TO 18
      IF(FF.EQ.0)GO TO 17
      ADD=ADD+1
      IF(ADD.GT.9)GO TO 25
      GO TO 17
  18  CONTINUE
      IF((NN.GT.9).AND.(ADD.LT.5))GO TO 25
      DO 13 JA=1,5
      RR(JA)=0
  13  CIR(JA)=0
      DO 14 JA=1,32
  14  NSAP(JA)=1
      TCIR=0
      TSPEN=0
      TLPEN=0
      ILPEN=0
      TCCT=0
      RDEL=0
      RTLP=0
      LL=0
      II=1
      DO 16 I=1,5
  16  NOTU(I)=0
  20  JJ=KA-(KA/2)*2
      KA=KA/2
      IF((JJ.EQ.0).AND.(KA.EQ.0))GO TO 45
      LL=LL+1
      IF(JJ.EQ.0)GO TO 20
      ICOMB(II,1)=PSA(LL)
      ICOMB(II,2)=LL
      NSAP(LL)=0
      IIMX=II
      H=ICOMB(II,1)/1000
      I=ICOMB(II,1)-H*1000
      DO 40 L=1,5
      IF(QIK(H,I,L).LE.RAIQT(L))GO TO 39
      WRITE(6,26)L,I,H
  26  FORMAT(//,10X,' ***** THE RESOURCES',I2,'  AVAILABLE DO NOT MEET T
     1HE NEEDS OF ACTIVITY ',I6,' OF PROJECT',I4)
      STOP
  39  RR(L)=RR(L)+QIK(H,I,L)
      IF(RR(L).GT.RAILT(L))GO TO 25
  40  CONTINUE
      IF(KA.EQ.0)GO TO 45
      II=II+1
      GO TO 20
  45  CONTINUE
C
C     THE COST OF IDLE RESOURCES FOR COMB. KK IS COMPUTED
C
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
      CTI=C
      DO 35 IL=1,5
      CTWR(IL)=0
      IF(RR(IL).GT.RA(IL))GO TO30
      CIR(IL)=(RA(IL)-RR(IL))*CS(IL)
      TCIR=TCIR+CIR(IL)
      GO TO 35
C
C     THE ADDITIONAL COST FOR OVERTIME WORK IS CALCULATED
C
   30 CCT(IL)=(RR(IL)-RA(IL))*CS(IL)*CF(IL)
      TCCT=TCCT+CCT(IL)
      CTI=CTI+1
      CTWR(CTI)=IL
      NOTU(IL)=NOTU(IL)+RR(IL)-RA(IL)
   35 CONTINUE
      U=TCIR+TCCT
      IF(U.GT.MINDEL)GO TO 25
C
C     COMPUTATION ACT. SPLITING PENALTY
C
      PEN=0
      IF(CD.EQ.1)GO TO 54
      DO 53 IL=1,NALC
      H=LCOMB(IL)/1000
      I=LCOMB(IL)-H*1000
      IF(CIK(H,I,6).EQ.0)GO TO 53
      DO 51 JA=1,IIMX
      IF(LCOMB(IL).EQ.ICOMB(JA,1))GO TO 53
   51 CONTINUE
      DO 52 JB=1,5
   52 TSPEN=TSPEN+SPEN(JB)*CIK(H,I,JB)
   53 CONTINUE
   54 CONTINUE
      RDEL=TSPEN+TCIR
      IF(RDEL.GT.MINDEL)GO TO25
C
C     LATENESS PENALTY FOR UNSCHEDULED CRITICAL ACT. IS COMPUTED
C
      DO 55 JA=1,S
      LPS(JA)=0
   55 ST(JA)=0
      DO 60 JA=1,NN
      IF(NSAP(JA).EQ.0)GO TO 60
      H=PSA(JA)/1000
      I=PSA(JA)-H*1000
      TEMP=ACCH(H,1,4)-(CIK(H,I,6)+CSLK(H))
      IF(TEMP.GE.CD)GO TO 60
      STR=CD-TEMP
      IF(STR.LE.ST(H))GO TO 60
      LPEN=(STR-ST(H))*LP(H)
      TLPEN=TLPEN+LPEN
      ST(H)=ST(H)+STR
      IF(CD.LE.ACCH(H,1,3))GO TO 60
      STL=CD-ACCH(H,I,3)
      IF(STL.LE.LPS(H))GO TO 60
      RLP=(STL-LPS(H))*LP(H)
      RTLP=RTLP+RLP
      LPS(H)=LPS(H)+STL
   60 CONTINUE
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
  912 CONTINUE
      IF(ICPA(A,3).EQ.PSA(JA))GO TO 903
      IF(JA.GE.NN)GO TO 904
      JA=JA+1
      GO TO 912
  903 CCPA(I,COUNT,1)=A
      CCPA(I,COUNT,2)=B
      CCPA(I,COUNT,3)=JA
      COUNT=COUNT+1
  904 B=B+1
      IF((ICPA(A,B).NE.0).OR.(B.LT.5))GO TO 902
      A=A+1
      IF(COUNT.LE.2)GO TO 901
      CNT(I)=COUNT-1
      I=I+1
      GO TO 901
C
C  FIND ALL THE POSIBLE COMBINATIONS AFTER ELEMINATE INCOMPATABLE ACTIV-
C  ITIES.
C
  905 III=0
      IF((I.EQ.1).AND.(COUNT.LE.1))GO TO 200
      III=I-1
      WRITE(6,215)(PPSA(JA),JA=1,NN)
  215 FORMAT(///,10X,' ***ORIGINAL POOL OF SCHE ACT CONTAINS : ',12I8,/'
     1 ',20I8)
      WRITE(6,603)
  603 FORMAT(10X,' *** FOLLOWING SETS OF ACTIVITIES ARE INCOMPATABLE: ')
      IF(III.EQ.0)GO TO 226
      DO 216 I=1,III
      IIN=CNT(I)
  216 WRITE(6,604)I,(PSA(CCPA(I,A,3)),A=1,IIN)
  604 FORMAT(42X,'SET ',I2,'.  ',5I5)
  226 Z=1
      DO 991 I=1,III
  991 Z=Z*CNT(I)
      K=Z
 1000 CONTINUE
      K=K-1
      Z=K
      DO 906 I=1,III
      P=Z/CNT(I)
      IN(I)=Z+1-P*CNT(I)
  906 Z=P
C
C  REMOVE INCOMPATABLE ACTIVITIES
C
      J=0
      DO 908 JA=1,NN
      DO 907 I=1,III
      IIN=CNT(I)
      DO 907 COUNT=1,IIN
      IF(JA.NE.CCPA(I,COUNT,3))GO TO 907
      IF(JA.NE.CCPA(I,IN(I),3))GO TO 908
  907 CONTINUE
      J=J+1
      PSA(J)=PPSA(JA)
  908 CONTINUE
      INCOMP=1
      N1=J
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
     2 20X,             '****************************************',//)
      DO 1 H=1,S
      M=N(H)
      CRIP(H)=0
      DO 101 I=1,M
  101 NIMP(H,I)=0
C
C  COUNT IMMEDIATE PREDECESSORS
C
      DO 1 I=1,M
      DO 1 J=1,5
      ACCH(H,I,J)=0
      CT=IMF(H,I,J)
      IF(CT.GT.0)NIMP(H,CT)=NIMP(H,CT)+1
    1 CONTINUE
      DO 2 H=1,S
      ACCH(H,1,1)=ARRD(H)
      ACCH(H,1,2)=ACCH(H,1,1)+CIK(H,1,6)
      M=N(H)
      DO 103 IT=1,M
      DO 102 J=1,5
      IF (IMF(H,IT,J).EQ.0)GO TO 103
      TIMF=IMF(H,IT,J)
      IF(ACCH(H,TIMF,1).GE.ACCH(H,IT,2))GO TO 102
      ACCH(H,TIMF,1)=ACCH(H,IT,2)
      ACCH(H,TIMF,2)=ACCH(H,TIMF,1)+CIK(H,TIMF,6)
  102 CONTINUE
  103 CONTINUE
      DO 4 P=1,250
    4 SA(P)=0
      CTO=0
      CTI=0
      TCIR=0
      DO 10 A=1,M
      IT=M+1-A
      IF(IMF(H,IT,1).NE.0)GO TO 10
      CRIP(H)=ACCH(H,IT,2)
      ACCH(H,IT,4)=DD(H)
      ACCH(H,IT,3)=ACCH(H,IT,4)-CIK(H,IT,6)
      ACCH(H,IT,5)=ACCH(H,IT,4)-ACCH(H,IT,2)
      I=IT
   13 CONTINUE
C
C  BACKWARDS PASS STARTS HERE
C
      CNT=0
      P=I-1
      IF(P.EQ.0)GO TO 112
      DO 312 I=1,P
      Z=I-1
      DO 12 J=1,5
      IF(IMF(H,Z,J).EQ.0)GO TO 312
      IF(IMF(H,Z,J).NE.T)GO TO 12
      CNT=CNT+1
      IF(ACCH(H,Z,4).NE.0)GO TO 50
      ACCH(H,Z,4)=ACCH(H,1,3)
      ACCH(H,Z,3)=ACCH(H,Z,4)-CIK(H,Z,6)
      ACCH(H,Z,5)=ACCH(H,Z,4)-ACCH(H,Z,2)
      CTI=CTI+1
      SA(CTI)=Z
```


THIS PAGE IS BEST QUALITY
FROM COPY FURNISHED TO DDC

```
   50 IF(ACCH(H,Z,4).LE.ACCH(H,I,3))GO TO 60
      ACCH(H,Z,4)=ACCH(H,I,3)
      ACCH(H,Z,3)=ACCH(H,Z,4)-QIK(H,Z,6)
      ACCH(H,Z,5)=ACCH(H,Z,4)-ACCH(H,Z,2)
      CTI=CTI+1
      SA(CTI)=Z
   60 IF(NIMP(H,I).EQ.CNT)GO TO 112
   12 CONTINUE
  312 CONTINUE
  112 CTO=CTO+1
      IF(CTO.GT.CTI)GO TO 2
      I=SA(CTO)
      GO TO 13
   10 CONTINUE
   2  CONTINUE
      WRITE(6,110)
  110 FORMAT(///,10X,' *** EXPECTED CRITICAL PATH COMPLETION DATE ***')
      DO 116 H=1,S
  116 WRITE (6,115)H,CRIP(H)
  115 FORMAT(/,10X,'CRITICAL PATH COMPLETION DATE OF PROJECT',I4
     1,' IS:',I4)
      RETURN
      END
C
C
C
      SUBROUTINE CHCAT(ACCH,PSA,RA,CSLK,CS,LP,CD,S,N,CCOMB,ICOMB,USACH,
     1 QIK,TSAV,LCOMB,NALC,IMF,ARRD,NIMP,JC,NACC,COMPD,NCOM,CF,COT,
     2 RAIOT,TOTWR,OTWR,ANOTU,TNOTU,NOTU,KATD,TT,DD)
      IMPLICIT INTEGER (A-Z)
      INTEGER ACCH(10,100,5),PSA(32),ICOMB(32,2),RR(5),RA(5),CIR(5),
     1 ST(10),NSAP(32),CSLK(10),CS(5),LP(10),CCOMB(32,2),TSAV(10,100),
     2 USACH(32),QIK(10,100,6),IMF(10,100,5),N(10),SPEN(5),LCOMB(32),
     3 ARRD(10),NIMP(10,100),COMPD(10),NCOM(10),CAC(32),RAIOT(5),
     4 TOTWR(5),OTWR(5),LPS(10),ANOTU(5),ICPA(100,5),TNOTU(5),NOTU(5)
     5,CCPA(10,5,3),CNT(10),IN(10),PPSA(32),KATD(30,2),RLFT(5,100,3)
     6,CRIP(10),DD(10)
      REAL OVT, DEL,MINDEL,TCOT,ATCOT,U,ADEL,T,RDEL,SQRT,X,Q,OVTR(5)
      REAL XSQ,RADEL,PDEL,CF(5),COT(5)
      DATA ICPA,CCPA/650*0/,RLFT/1500*0/
C  RA(L) : NUMBER OF UNITS AVAIABLE OF RESOURCE TYPE L.
C  RAILT : RA WITH OVERTIME.
C  PSA : SCHEDULABLE ACTIVITIES ON THE DATE CONSIDERED.
C  COMPD(H) : COMPLETION DATE OF PROJECT H
C  ICPA : ARRAY STORE INCOMPARABLE ACTIVITIES.
C  CCPA:  ARRAY CONTAINS INCOMPARABLE ACTIVITIES IN THE POOL OF SCHE. AC
C  RLFT : RESOURCE LEVEL FROM TO
C  OVTR : OVERTIME RATIO (PERCENT) ALLOWED
C  III : NUMBER OF INCOMPATABLE SETS
C
C
C  INPUT RESOURCE LEVEL
C
      WRITE(6,63)
   63 FORMAT(1H1,19X,'*********************************************',/,
     1            20X,'** RESOURCE AVAILABLE AND ASSOCIATED COSTS   **',/,
     2 20X ,         '*********************************************',//
     3/)
      WRITE(6,160)
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
      C   XAT  ,I(  ' *   RES  RCE   VEL   *'
          J=1
          XSS=0
          INCOMP=0
      150 READ(3,151)A,B,C,D
      151 FORMAT(415)
          IF(A.EQ.9999)GO TO 153
          RLFT(A,J,1)=B
          RLFT(A,J,2)=C
          RLFT(A,J,3)=D
          WRITE(6,161)A,C,D,B
      161 FORMAT(/,10X,' RESOURCE',I2,' : FROM DATE',I3,' TO',I3,' THERE ARE
         1',I4,' UNITS AVAILABLE')
          J=J+1
          GO TO 150
C
C    INPUT OVERTIME RATIO (FOR MAX OVERTIME)
C
      153 READ(3,154)OVTR
      154 FORMAT(5F5.2)
          WRITE(6,162)(I,OVTR(I),I=1,5)
      162 FORMAT(////,10X,' ***MAX. OVER TIME AVAILABLE ***',/,
         1//,(10X,' FOR RESOURCE',I2,' PERCENTAGE OF OVERTIME IS',F5.2,/))
          RL=J
C
C    INPUT COSTS INFORMATION
C
          READ(3,2)(CS(L),L=1,5)
          READ(3,2)(SPEN(L),L=1,5)
        2 FORMAT(5I5)
          READ(3,621)(CF(L),L=1,5)
      621 FORMAT(5F6.2)
          WRITE(6,4)(L,L=1,5),CS,SPEN,CF
        4 FORMAT(///,20X,' *** COSTS INFORMATION ***',//,
         1            10X,'RESOURCES                ',5I6,//,
         2            10X,'UNIT COST                ',5I6,//,
         3            10X,'SPLITTING PENALTY        ',5I6,//,
         4            10X,'OVERTIME COST FACTOR     ',5F6.2,/)
C
C    INPUT INCOMPATABLE RELATIONSHIPS
C
          DO 211 I=1,100
          READ(3,2)(ICPA(I,L),L=1,5)
          IF(ICPA(I,1).EQ.0)GO TO 602
      211 CONTINUE
      602 CONTINUE
          I=I-1
          IF(I.EQ.0)GO TO 750
          WRITE(6,666)(J,(ICPA(J,L),L=1,5),J=1,I)
      666 FORMAT(1H1,19X,'**********************************',/,20X,
         1               '**    INCOMPATIBLE ACTIVITIES    **',/,20X,
         2               '**********************************',//,
         3(I13,'.',3X,5I6,/))
      750 CONTINUE
          CALL LAMDA(IMP,ACCP,NIMP,LIK,ARRD,N,S,CRIP,LD)
          DO 1 JA=1,32
        1 PSA(JA)=0
          DO 6 H=1,S
          COMPD(H)=0
        6 NCOM(H)=0
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
      ADEL=0
      ATCIR=0
      ATSPEN=0
      ATLPEN=0
      ATCCT=0
      XSC=0
      XAV=0
      NN=0
      DO 102 I=1,5
      TNDTU(I)=0
  102 ANDTU(I)=0
      CD=1
      WRITE(6,7)
    7 FORMAT(1H1,19X,     '****************************************',/
     1,20X,               '*****                              *****',/,
     220X,                '*****   SCHEDULE OF ACTIVITIES     *****',/,
     320X,                '*****                              *****',/,
     420X,                '****************************************',///)
C
C   ACTIVITIES WITH NO IMM. PRE. ARE ADDED TO THE POOL
C
      DO 10 H=1,S
      M=N(H)
      DO 12 I=1,M
      IF(ACCH(H,I,1).GT.1)GO TO 10
      NN=NN+1
      PSA(NN)=1000*H+I
   12 CONTINUE
   10 CONTINUE
C
C   ALL POSSIBLE COMBINATIONS ARE COMPUTED
C
   11 MINDEL=1.E30
      N1=NN
C
C   FIND THE RESOURCE AVAILABLE
C
      DO 300 I=1,5
      DO 301 J=1,RL
      IF((CD.GE.RLFT(I,J,2)).AND.(CD.LE.RLFT(I,J,3)))GO TO 310
  301 CONTINUE
  310 RA(I)=RLFT(I,J,1)
      CVT=RLFT(I,J,1)*CVTR(I)
      RAICT(I)=CVT
  300 CONTINUE
      DO 890 I=1,10
      DO 890 J=1,5
      DO 890 K=1,3
  890 CCPA(I,J,K)=0
      DO 900 JA=1,NN
  900 FPSA(JA)=PSA(JA)
      I=1
      A=1
  901 CCUNT=1
      B=1
      IF(ICPA(A,1).LT.1)GO TO 905
C
C   FIND ACTIVITIES WHICH HAVE INCOMPATABILITY RELATIONSHIP FROM POOL
C
  902 JA=1
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
    4 M=N(H)
    3 CONTINUE
C
C   INPUT IMEDIATE FOLLOWERS OF ACTIVIES.
C
      READ(5,502)K,IMF1,IMF2,IMF3,IMF4,IMF5
  502 FORMAT(6I5)
      IF(K.EQ.99999)GO TO 6
      IF(K.EQ.0)GO TO 2
      IMF(H,K,1)=IMF1
      IMF(H,K,2)=IMF2
      IMF(H,K,3)=IMF3
      IMF(H,K,4)=IMF4
      IMF(H,K,5)=IMF5
      L=1000*H+K
      DO 5 J=1,5
      IF(IMF(H,K,J).EQ.0)KK(J)=0
    5 IF(IMF(H,K,J).GT.0)KK(J)=1000*H+IMF(H,K,J)
      WRITE(6,801)L,KK
  801 FORMAT(12X,I4,3X,5I9)
      GO TO 3
    6 KATD(TT,1)=IMF1+1000*H
      KATD(TT,2)=IMF2
      WRITE(6,665)(KATD(TT,J),J=1,2)
  665 FORMAT(/,10X,' **KEY ACTIVITY',I5,' HAS TARGET DATE OF',I3)
      TT=TT+1
      GO TO 3
    2 CONTINUE
C
C   INPUT RESOURCES REQUIREMENT AND ACTIVITY DURATION.
C
      TT=TT-1
      DO 7 H=1,S
      M=N(H)
      DO 7 I=1,M
      TSAV(H,I)=0
      DO 7 K=1,6
    7 QIK(H,I,K)=0
      WRITE(6,802)
  802 FORMAT(1H1,19X,' ***********************************************
     1****',/,20X,    ' **  RESOURCES REQUIREMENT AND ACTIVITIES DURATION
     2  **',/,20X,    ' ***********************************************
     3****',///,10X,' ACTIVITY NO      RES 1  RES 2  RES 3  RES 4  RES 5
     4  DURATION',/)
C
C   READ PROJECT NUMBER
C
      DO 8 H=1,S
      READ(2,503)A,HK
  503 FORMAT(A2,I3)
      M=N(HK)
      DO 9 I=1,M
      READ(3,504)J,(QIK(HK,I,K),K=1,6)
  504 FORMAT(7I5)
      L=1000*HK+I
      TSAV(HK,I)=QIK(HK,I,6)
      DO 410 K=1,6
  410 TP(K)=QIK(HK,I,K)
    9 WRITE(6,603)L,TP
  603 FORMAT(13X,I4,7X,6I7)
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

```
       9 CONTINUE
C
C     COMPUTE THE RESOURCE REQUIREMENTS
C     TRR: TOTAL RESOURCE REQUIREMENTS
C     CIK(H,I,K):  H: PROJECT
C                  I: ELEMENTS
C                  J: RESOURCE
C
         DO 11 J=1,5
      11 TRR(J)=0
         WRITE(6,63)
      63 FORMAT(///,10X,'*** TOTAL RESOURCE REQUIREMENT ***',/)
         DO 12 H=1,S
         M=N(H)
         DO 12 J=1,5
         DO 12 I=1,M
         TRR(J)=TRR(J)+CIK(H,1,6)*CIK(H,I,J)
      12 CONTINUE
         WRITE(6,40)(TRR(J),J,J=1,5)
      40 FORMAT(//,10X,' A TOTAL OF ',I9,' UNIT-DAYS ARE REQUITED OF RES',
        1I4)
C
C     CALL SUBROUTINE CHCAT TO SCHEDULE ACTIVITIES.
C
         CALL CHCAT(ACCH,PSA,RA,CSLK,CS,LP,CD,S,N,CCOME,ICOME,USACH,
        1CIK,TSAV,LCOMB,NALC,IMF,ARRD,NIMP,JC,NACC,CCMPD,NCOM,CF,CCT,
        2RAICT,TOTWR,OTWR,ANCTU,TNCTU,NOTJ,KAID,IT,DD)
C
C     CALL SUBROUTINE STATIS TO COLLECT STATISTICS.
C
         CALL  STATIS(S,N,TRR,RA,CD,CS,COMPD,ARRD,CRIP,DD,ANCTU)
         STOP
         END
C
C
C
         SUBROUTINE LAMDA(IMF,ACCH,NIMP,CIK,ARRD,N,S,CRIP,DD)
C
C    SUBROUTINE TO COMPUTE THE CRITICAL PATH LENGTH ,ES,EF,LS,LF,AND SLACK
C
         IMPLICIT INTEGER (A-Z)
         INTEGER IMF(10,100,5),ACCH(10,100,5),NIMP(10,100),CIK(10,100,6)
        1,ARRD(10),N(10),SA(250),COMP(100),CRIP(10),DD(10),CHK(100)
         INTEGER TIMF,CT,L,IT
C
C     ACCH(H,I,J)
C                   J=1 : ES
C                     2 : EF
C                     3 : LS
C                     4 : LF
C                     5 : TS
C     IMF(H,I,J)
C                   J : IMMEDIATE FOLLOWERS OF ACTIVITY I
C     NIMP(H,CT) : NUMBER OF IMMEDIATE PREDECESSORS OF ACTIVITY CT
C     ARRD(H)    : ARRIVING DATE
C
         WRITE(6,500)
     500 FORMAT(////,20X,'**************************************',/,
        1 20X,         '**          NETWORK SOLUTION          **',/,
```


THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC

Official distribution list for the technical, annual, and final reports for Contract N00014-78-C-0411.

Defense Documentation Center Cameron Station Alexandria, VA 22314	12 copies
Office of Naval Research Arlington, VA 22217	
Information Systems Program (437)	2 copies
Code 434	1 copy
Code 200	1 copy
Code 455	1 copy
Code 458	1 copy
Office of Naval Research Branch Office, Boston Bldg. 114, Section D 666 Summer Street Boston, MA 02210	1 copy
Office of Naval Research Branch Office, Chicago 536 South Clark Street Chicago, IL 60605	1 copy
Office of Naval Research Branch Office, Pasadena 1030 East Green Street Pasadena, CA 91106	1 copy
Office of Naval Research New York Area Office 715 Broadway - 5th Floor New York, NY 10003	1 copy
Naval Research Laboratory Technical Information Division, Code 2627 Washington, D.C. 20375	6 copies
Dr. A. L. Slafkosky Scientific Advisor Commandant of the Marine Corps (Code RD-1) Washington, D.C. 20380	1 copy
Naval Ocean Systems Center Advanced Software Technology Division Code 5200 San Diego, CA 92152	1 copy
Mr. E. H. Gleissner Naval Ship Research & Development Center Computation and Mathematics Department Bethesda, MD 20084	1 copy
Commanding Officer Fleet Material Support Office Mechanicsburg, PA 17055	3 copies